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Quantifying Disparities in Per- and Polyfluoroalkyl Substances (PFAS) Levels in Drinking Water from Overburdened Communities in New Jersey, 2019–2021

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Background: Policymakers have become increasingly concerned regarding the widespread exposure and toxicity of per- and polyfluoroalkyl substances (PFAS). While concerns exist about unequal distribution of PFAS contamination in drinking water, research is lacking.

Objectives: We assess the scope of PFAS contamination in drinking water in New Jersey (NJ), the first US state to develop regulatory levels for PFAS in drinking water. We test for inequities in PFAS concentrations by community sociodemographic characteristics.

Methods: We use PFAS testing data for community water systems (CWS) ($n = 491$) from the NJ Department of Environmental Protection (NJDEP) from 2019 to 2021 and demographic data at the block group level from the US Census to estimate the demographics of the NJ population served by CWS. We use difference in means tests to determine whether CWSs serving "overburdened communities" (OBCs) have a statistically significant difference in likelihood of PFAS detections. OBCs are defined by the NJDEP to be census block groups in which: *a*) at least 35% of the households qualify as low-income, *b*) at least 40% of the residents identify as people of color, or *c*) at least 40% of the households have limited English proficiency. We calculate statewide summary statistics to approximate the relative proportions of sociodemographic groups that are served by CWSs with PFAS detections.

Results: We find that 63% of all CWSs tested by NJDEP from 2019 to 2021 had PFAS detections in public drinking water, collectively serving 84% of NJ's population receiving water from CWSs. Additionally, CWSs serving OBCs had a statistically significant higher likelihood of PFAS detection and a higher likelihood of exposure above state MCLs. We also find that a larger proportion of people of color lived in CWS service areas with PFAS detections compared to the non-Hispanic white population.

Discussion: These findings quantitatively identify disparities in PFAS contamination of drinking water by CWS service area and highlight the extent of PFAS drinking water contamination and the importance of PFAS remediation efforts for protecting environmental health and justice. https://doi.org/10.1289/EHP12787

Introduction

Despite growing public health concerns regarding the widespread exposure and toxicity of per- and polyfluoroalkyl substances (PFAS), little is known about how PFAS exposure through drinking water is distributed across the US population. Decades of research have shown that environmental hazards, including exposure to toxic substances and unsafe drinking water, are disproportionately experienced according to race and ethnicity, socioeconomic status, English-language proficiency, and other forms of marginalization.[1–5] Previous research on other contaminants in drinking water have focused on community water system (CWS) compliance with the Safe Drinking Water Act (SDWA), while fewer studies use contaminant concentrations, to show disparities by the racial and/or ethnic composition of the served population.[6–10]

Given historical evidence of disproportionate pollution exposure and the multiple mechanisms that can create drinking water disparities,[11] there is reason to suspect PFAS contamination in community drinking water may also be inequitably experienced. PFAS contamination is associated with the presence of military, airport, and industrial facilities,[12,13] which are disproportionately located proximal to marginalized communities due to systemic inequalities including historical discrimination in redlining, housing laws, and inequitable enforcement of environmental regulations.[14–16]

Some research has documented correlations between population demographics and PFAS exposure identified with biomonitoring data, though results have been mixed.[17–19] Liddie et al. geocoded CWSs within larger hydrologic units and found that CWSs serving counties with higher proportions of Hispanic/Latino and non-Hispanic black residents had higher odds of PFAS detections, likely reflecting the location of PFAS contamination sources.[12] No known peer-reviewed quantitative publications investigate environmental justice concerns related to PFAS in drinking water by linking PFAS detections in CWSs to resident demographics at the block group level.

PFAS are a broad class of persistent, anthropogenic chemicals used in consumer products and industrial processes. Widespread use, resistance to degradation, and lack of federal regulation of chemical use and disposal has resulted in extensive PFAS contamination across the United States.[20] There are over 12,000 PFAS in the large chemical class,[21] and the compounds are used in over 200 use categories across consumer and industrial applications.[22] Perfluorooctane sulfonate (PFOS) and perfluorooctanoic acid (PFOA) are the most known and well investigated PFAS. Perfluorononanoic acid (PFNA) is also a focus of regulatory attention in New Jersey (NJ), due to the location of a chemical plant identified as the second largest industrial producer of PFNA in the world.[23]

Human exposure to certain PFAS is nearly universally measured in representative biomonitoring studies,[24] and has been associated

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with a variety of health effects, including kidney and testicular cancer, immune system hypersensitivity and suppression, endocrine disruption, and adverse reproductive outcomes.[25–32] Among the many possible exposure pathways,[33] consuming contaminated drinking water is of particular concern. An estimated 200 million US residents receive drinking water contaminated with PFAS.[34] PFAS are nearly ubiquitous in surface water,[35] which is the most common water source for large CWSs, but PFAS are also commonly found in groundwater wells, the primary water source for many smaller communities. Biomonitoring studies have found PFAS in public drinking water to be a significant predictor of PFAS blood serum concentrations.[36,37] Additionally, even relatively low levels in drinking water can contribute a greater proportion to serum concentrations than other ubiquitous sources such as consumer products.[38,39]

The United States Environmental Protection Agency (USEPA) conducted national testing of large CWSs for six PFAS as part of the Third Unregulated Contaminant Monitoring Rule (UCMR3),[40] but no nationwide testing was conducted from 2015 to 2022. While the USEPA has the authority to set federal standards for drinking water contaminants, there are currently no enforceable federal drinking water standards for any PFAS, leading states to develop their own regulatory or screening levels for PFAS in public drinking water.[41] In 2018 New Jersey adopted the first state-level maximum contaminant level (MCL) for any PFAS (PFNA: 13 ng/L), with monitoring starting in 2019.[42,43] By the end of 2020, the NJ Department of Environmental Protection (NJDEP) required testing for all CWSs across the state for PFNA except for systems entirely reliant on purchased water, since that water must be tested by the CWS where it originates. In 2020, the state adopted two more MCLs (PFOA: 14 ng/L and PFOS: 13 ng/L), with required monitoring starting in 2021. In March 2023, the USEPA proposed federal MCLs for six PFAS, including those regulated in New Jersey,[44] and if finalized, standards for these PFAS will go into effect 3 years later (barring exemptions).[45] The supplemental files include a timeline of additional US and NJ events relevant to this analysis [Supplemental Materials, "Timeline of Notable PFAS Regulations in the US and New Jersey (NJ)"].

Mandatory statewide testing by NJDEP, the first state to adopt a regulatory MCL for any PFAS[43] and thus require PFAS testing for all CWSs, provides an opportunity to examine the distribution of PFAS contamination in municipal water supplies by sociodemographic characteristics and to identify trends in PFAS detections over time. In this study, we use 2019–2021 CWS testing data from NJDEP and demographic data at the Census block group level to assess the scope of PFAS contamination in NJ drinking water. The study is representative of all NJ CWSs except those reliant entirely on water purchased from other CWSs.

Methods

We assessed the scope of PFAS contamination in community drinking water in New Jersey and analyzed the sociodemographic characteristics of the exposed population using 2019–2021 CWS PFAS testing data from NJ Department of Environmental Protection (NJDEP) and demographic data at the census block group level from the 2016–2020 American Community Survey (ACS). Census block groups are divisions of census tracts which typically contain between 600 and 3,000 people. From 2019 to 2021, NJDEP tested water samples for PFAS from 496 CWSs from 1,207 unique sample locations. Sample locations include groundwater wells, surface water intakes, common headers, treatment plants, interconnections, and distribution systems. Data on the spatial boundaries of CWS service areas, primary water source, population served, and sample location type were obtained from NJDEP.[46,47]

At least four quarters of samples were collected from each CWS ($n = 491$). This dataset represents an "unbalanced panel" because CWSs can have different numbers of samples based on state testing requirements (e.g., CWSs may be allowed to reduce testing frequency if they are repeatedly in compliance with MCLs). We calculated four-quarter rolling average values from each sample location for PFNA, PFOA, and PFOS since NJDEP uses rolling averages to determine MCL violations. (Although CWSs were not technically required to monitor for PFOA and PFOS before 2021, more than 95% of systems also reported PFOA and PFOS in 2019–2020, and roughly half reported additional unregulated PFAS.) Five CWSs were dropped because of missing geographic information. A complete list of CWSs in New Jersey and indicators for whether they were sampled for PFAS in either UCMR3 or by NJDEP is included in Excel Table S1. Excel Table S1 also includes the number of samples collected and information about whether geographic information is available for each CWS.

Minimum reporting levels (MRLs) (below which "nondetect" rather than a number is recorded) vary based on laboratory methods and capabilities.[48] About 94% of NJDEP samples reported MRLs ≤ 2 ng/L, and most remaining samples reported MRLs ≤ 5 ng/L. We imputed 0 ng/L for nondetects. See Tables S2 and S3 for more details on MRLs and the laboratory methods used to detect PFAS.

NJDEP MCL testing required samples of the "finished" water that is delivered to customers. Some CWSs have samples of both raw and treated water, and for these CWSs, we excluded the raw water samples. However, some small CWSs do not have water treatment and thus deliver "raw" water (about 8% of CWSs, but serving just 0.1% of the population).

We calculated summary statistics reported in NJDEP testing for all samples, the maximum detections within each tested CWS, and the estimates of the population served within each CWS characteristic. The population served for each water system is a static number reported to NJDEP and collected from New Jersey's Drinking Water Watch database in 2022. We also summarized samples by primary water source, water system size, and whether the sample was from a treated or raw source.

We present PFAS levels detected within individual CWS water samples using several indicators, including: "Any PFAS Detected" (which includes detected values of any of the 12 reported PFAS), "PFNA Detected," "PFOA Detected," "PFOS Detected," "Above NJ MCL" [an indicator if at least one of the NJ MCLs (13 ng/L for PFNA, 13 ng/L for PFOS, and 14 ng/L for PFOA) was exceeded], and "Above EPA Proposed MCL" [an indicator if at least one of the PFAS regulated in NJ exceeded the EPA's proposed MCLs (10 ng/L for PFNA, 4 ng/L for PFOA, and 4 ng/L for PFOS)]. (The proposed EPA MCL for PFNA is based on a combined "Hazard Index" for PFNA, perfluorobutane sulfonate (PFBS), hexafluoropropylene oxide dimer acid (HFPO-DA, commonly known as Gen X), and perfluorohexane sulfonate (PFHxS), which is unitless based on a formula comparing the concentration of each contaminant to the highest level determined not to have risk of health effects. For PFNA alone, the MCL would be 10 ng/L.[44]) To calculate exceedances of NJ MCLs, we used the maximum running annual average of four consecutive quarters of results within a sample location for each CWS, which approximates NJDEP violations. Indicator variables were created equal to 1 if PFAS levels exceed the threshold and equal to 0 otherwise.

To explore differences in PFAS detections based on drinking water source, we analyzed whether PFAS contamination varied for systems that primarily rely on surface water vs. those primarily reliant on groundwater. We also explored differences in PFAS detections by water system size.

We report PFAS detections and exceedances above NJ MCLs and EPA proposed MCLs as proportions both of CWSs and of the population served. To investigate the demographic characteristics of populations served by CWSs, we used the NJ definition of "overburdened communities" (OBCs).[49] NJ designates a census block group as an OBC if the proportion of people of color (defined as all populations other than non-Hispanic whites) exceeds 40%, if the proportion of low-income households (defined as below two times the federal poverty level) exceeds 35%, or if the proportion of limited English households (defined as households without at least one person who speaks "good" English as reported to the US Census) exceeds 40%.[49]

We focused the analysis on CWS boundaries rather than other administrative boundaries, such as zip codes, since regulation and enforcement of PFAS in drinking water happens at the CWS level. Using US Census data from the 2016–2020 ACS, we calculated the OBC status for each census block group. We then determined whether each CWS served an OBC using the shapefiles for the CWS service area boundaries, available from NJDEP.[47] We intersected the CWS service areas boundaries with block group boundaries using the sf package in R version 4.0.4.[50] We defined a CWS as serving an OBC if at least one census block group that intersected its service area was characterized as an OBC based on the definitions determined by NJDEP. If one OBC block group was served by two CWSs, both CWSs were classified as serving an OBC. Figure 1 depicts OBCs by census block group and depicts CWSs that serve at least one OBC (Figure 1; Table S4). We performed difference in means tests based on OBC status of CWSs to compare characteristics and PFAS detections for OBC-serving vs. non-OBC-serving CWSs. For all analyses, we report p-values and use a statistical significance threshold of $p < 0.05$.

In addition to classifying CWS service areas by OBC status, we also estimated the overall demographic characteristics of the population served by CWSs. This allows us to estimate more detailed demographics of the population within CWS service areas with PFAS detections. We performed a spatial join of CWS service area boundaries and census block group boundaries using the sf package in R version 4.0.4.[50] We then calculated the areas of intersecting polygons and calculated the estimated demographics of CWS service areas using data from the 2016–2020 ACS based on the proportion of each block group served by each CWS. For block groups served by multiple CWSs, we assigned the proportion of the block group to the intersecting area of each CWS. For each demographic group of interest, we estimated the relative proportions of the total population for each group residing within the spatial boundaries of a CWS service area. We then used this proportion scaled by the population served by each CWS to estimate the demographic characteristics of the population served by each CWS. In addition to the OBC definitions for people of color, low-income, and limited English, we also included disaggregated race and ethnicity variables capturing the proportion of the population that is non-Hispanic white, Hispanic, non-Hispanic black, and non-Hispanic Asian using data from the 2016–2020 ACS (Table: B03002).[51] We used these data to estimate the proportions of each demographic group residing within CWS service areas that had PFAS detections as

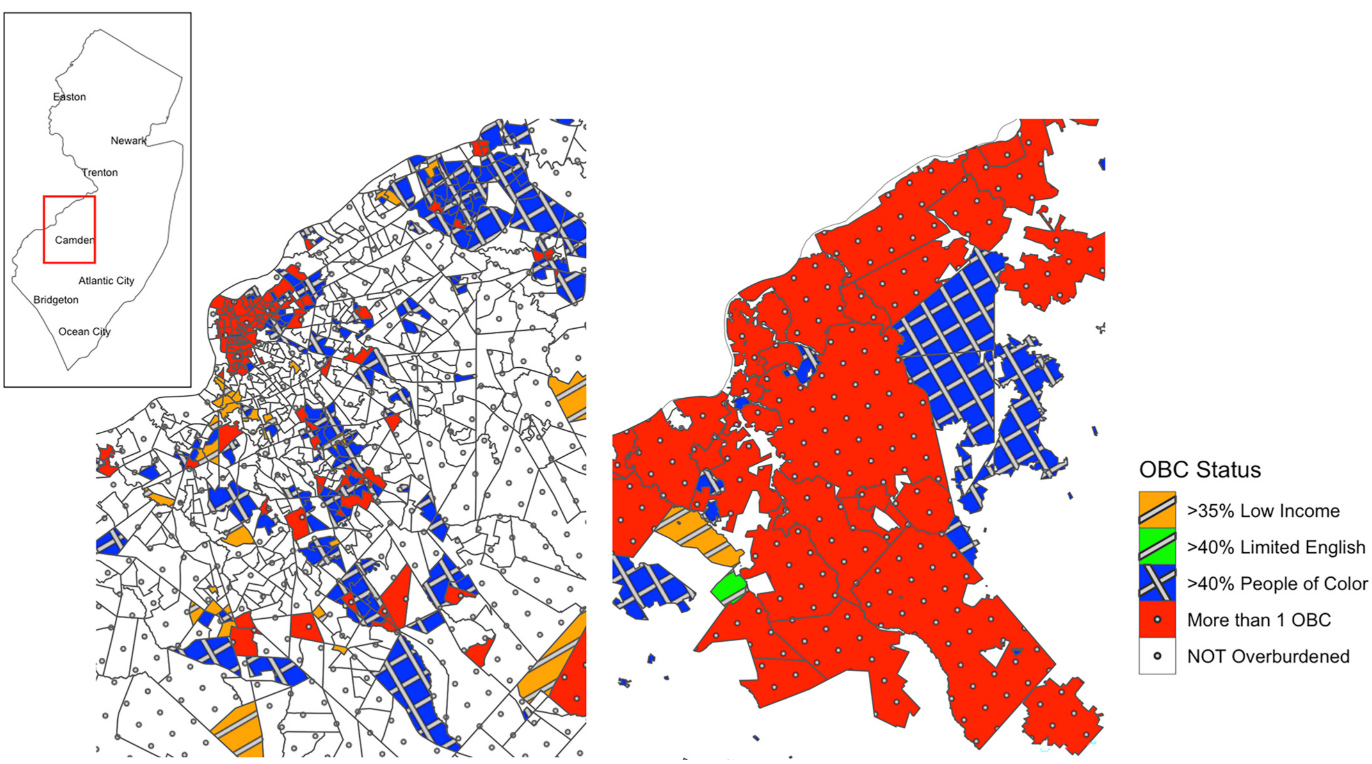

Figure 1. New Jersey overburdened communities (OBC). (A) Block groups. (B) CWS service areas. Figure 1 depicts OBC status as defined by the New Jersey Department of Environmental Protection (NJDEP) by census block group in panel A and aggregated to community water system (CWS) service area in panel B, zoomed into a portion of southwest New Jersey near Camden as an example. A block group is classified as an OBC by NJDEP if *a*) at least 35% of the households qualify as low income, *b*) at least 40% of the residents identify as people of color, or *c*) at least 40% of the households have limited English proficiency. "More than 1 OBC" denotes that the block group meets more than one OBC category. "NOT Overburdened" denotes that the block group does not meet any of the qualifications of an overburdened community. In panel B, CWSs are depicted by OBC status determined by whether the CWS serves at least one block group that is classified as an OBC. Data for this figure are described in Table S4.

described above. We also estimated the population within CWSs excluded from NJDEP testing because of their reliance on purchased water, and the population outside of CWS service areas, which approximates the demographics of the population reliant on private wells.

We replicated the analyses described above using UCMR3 testing data ($n = 165$ CWS), and we report and discuss these UCMR3 findings in the supplemental files [Supplemental Materials, "Discussion of Results from USEPA's Third Unregulated Contaminants Monitoring Rule (UCMR3)," Tables S5, S6, S9, and S10]. We separated these analyses for several reasons: *a*) Significant differences exist in the scale of UCMR3 and NJDEP testing in terms of number of included CWSs and the population served; *b*) UCMR3 testing had MRLs much higher than average MRLs used in NJDEP testing, making results difficult to compare.

Finally, to analyze whether PFAS contamination in CWSs has changed, we estimated logistic and linear regressions to determine how the likelihood of PFAS detections and detections above NJ MCLs have changed across the 12 quarters of NJDEP testing from 2019 to 2021. We estimated two logistic regressions where the dependent variable represents an indicator for whether PFAS was detected above MRLs or above NJDEP MCLs. For comparison and ease of interpretation, we also estimated a linear probability model with the same dependent variables.[52] Additionally, we estimated linear regressions where the dependent variables were the numerical values of PFNA, PFOS, and PFOA detected in nanograms per liter. All models included the quarter of testing (Quarterly Trend) to estimate the average quarterly change in likelihood of PFAS detection for all CWSs reporting to NJDEP. We also included interaction terms with the quarter of testing to estimate the additional change in likelihood of PFAS detection for CWSs that serve OBCs (Quarterly Trend × OBC) and the additional change in likelihood of PFAS detection for CWSs that have installed or are actively installing PFAS-specific water treatment (Quarterly Trend × Treatment). The data on PFAS-specific water treatment were obtained by data request from NJDEP and identify the CWSs that have applied for temporary or permanent permits to install PFAS-specific water treatment. The exact timing of completions of these installations was not reported, so these data should be interpreted as indicating CWSs that are actively working to remediate PFAS in drinking water, whether or not remediation is complete. We included sample location fixed effects to control for all characteristics of CWSs and specific sample locations that are constant over time, such as system size, water source, location, and demographics of population served. The inclusion of sample location fixed effects means the coefficient estimates can be interpreted as the average of within-sample-location changes over time. We did not include additional confounding variables in this analysis, as the sample location fixed effects restricts the coefficient estimates to the average trend across sample locations.

Results

Table 1 reports PFAS detections and exceedances of NJ MCLs from all NJDEP PFAS testing of CWSs from 2019 to 2021. Column 1 reports all unique samples, reflecting multiple samples from multiple quarters within a CWS, including samples from multiple sample locations within a CWS. Column 2 aggregates data to the CWS level, reflecting detections and maximum four-quarter average sample values of delivered water for each CWS. Column 3 reports estimates of proportions of the population receiving water with PFAS detections (Table 1).

Of all CWSs tested for PFAS by NJDEP from 2019 to 2021, at least one PFAS was detected in 63% of systems, providing water to 84% of the population served. Nearly 23% of New Jersey residents were served by CWSs with drinking water samples above at least one of NJ's PFAS MCLs (calculated on a four-quarter rolling average) at some point from 2019 to 2021, and 72% were served by CWSs with detections above the EPA's proposed MCLs. Notably, rates of detections are highest for PFOA and PFOS. Similar summary statistics for PFAS detections from UCMR3 testing (2013–2015) are reported in Table S5 and discussed in the supplemental files.

Table 2 reports PFAS detections by primary water source to distinguish between systems reliant on groundwater vs. surface water. While more CWSs primarily source from groundwater, surface water is the primary water source for most large CWSs in New Jersey, so the majority of the population receives drinking

Table 1. Characteristics of NJDEP PFAS testing (2019–2021).

Characteristic	All samples	Unique CWS	Population served
Total no.	7,747	491	7,943,046
Groundwater	70.6%	79.6%	28.2%
Surface water	7.6%	4.7%	50.6%
Purchased surface water	21.0%	14.5%	19.5%
Water treatment	92.3%	91.9%	99.9%
Any PFAS detected	55.2%	62.7%	83.9%
PFNA detected	8.7%	17.9%	31.1%
PFOA detected	52.2%	59.3%	81.1%
PFOS detected	43.3%	53.8%	76.3%
Above NJ MCL (4Qavg)	7.6%	13.6%	22.7%
Above EPA proposed MCL	42.2%	48.1%	71.8%

Note: Data include PFAS samples for all community water systems (CWSs) tested by New Jersey Department of Environmental Protection (NJDEP). Column 1 reports all unique samples, reflecting multiple samples from multiple quarters within a CWS and/or samples from multiple sample locations within a CWS. Column 2 aggregates data to the CWS level, reflecting maximum detections and maximum four-quarter average sample values of delivered water for each CWS. Column 3 reports estimates of populations served by tested water systems as reported by NJDEP's Drinking Water Watch. "Above NJ MCL (4Qavg)" indicates a four-quarter average PFAS sample exceeded at least one of NJ's maximum contaminant levels (MCLs) for PFAS (13 ng/L for PFNA, 13 ng/L for PFOA, or 14 ng/L for PFOS.) "Above EPA's Proposed MCL" indicates that a sample exceeded at least one of the United States Environmental Protection Agency's (USEPA's) proposed MCLs (4 ng/L for PFOA, 4 ng/L for PFOS, or 10 ng/L for PFNA). Ten nanograms per liter for PFNA would be the level of PFNA only needed to exceed the hazard index of 1.0. PFAS, per- and polyfluoroalkyl substances; PFNA, perfluorononanoic acid; PFOA, perfluorooctanoic acid; PFOS, perfluorooctane sulfonate.

Table 2. PFAS detections in NJDEP testing (2019–2021) by primary water source.

	Groundwater		Surface water	
	Unique CWS	Population	Unique CWS	Population
Total no.	391	2,238,683	94	5,572,084
Any PFAS detected	57.0%	54.5%	84.0%	95.3%
PFNA detected	13.6%	22.5%	34.0%	33.4%
PFOA detected	54.2%	51.5%	77.7%	92.6%
PFOS detected	49.1%	51.0%	71.3%	86.0%
Above NJ MCL (4Qavg)	11.5%	10.1%	23.4%	28.3%
Above EPA proposed MCL	43.2%	47.7%	67.0%	81.4%

Note: Data include PFAS samples for all tested community water systems (CWSs) by New Jersey Department of Environmental Protection (NJDEP). Columns 1 and 3 aggregate data to the CWS level, reflecting maximum detections and maximum four-quarter rolling average sample values of delivered water for each CWS. Columns 2 and 4 report estimates of population exposure to PFAS detected in municipal drinking water. CWSs who rely on purchased surface water as their primary water source are included in the Surface Water category in Table 1. However, systems with a primary water source of purchased groundwater or "Groundwater under the influence of surface water" (six CWSs in NJDEP) were excluded from Table 2. "Above NJ MCL (4Qavg)" indicates a four-quarter average PFAS sample exceeded at least one of NJ's MCLs for PFAS (13 ng/L for PFNA, 13 ng/L for PFOA, or 14 ng/L for PFOS). "Above EPA's Proposed MCL" indicates that a sample exceeded at least one of the United States Environmental Protection Agency's (USEPA's) proposed MCLs (4 ng/L for PFOA, 4 ng/L for PFOS, or 10 ng/L for PFNA). Ten nanograms per liter for PFNA would be the level of PFNA only needed to exceed the hazard index of 1.0. —, no data; MCL, maximum contaminant levels; PFAS, per- and polyfluoroalkyl substances; PFNA, perfluorononanoic acid; PFOA, perfluorooctanoic acid; PFOS, perfluorooctane sulfonate.

water from surface water sources. Eighty-four percent of CWSs reliant on surface water and 57% of CWSs reliant on groundwater had detected PFAS, representing 95% and 54% of the populations served, respectively. Twenty-three percent of CWSs reliant on surface water and 12% reliant on groundwater had exceedances above at least one NJ MCL, and 67% reliant on surface water and 43% reliant on groundwater were served by CWSs with exceedances above the EPA's proposed MCLs. Thus, surface water sources were more likely to have detectable levels of PFAS, though groundwater sources were also commonly found to have elevated levels of PFAS (Table 2). A comparable analysis based on UCMR3 testing (2013–2015) is reported in Table S6. Table S7 reports PFAS detections and CWS characteristics by CWS size. Small or very small systems were less likely to detect any PFAS or elevated PFAS levels, compared to medium, large, or very large systems.

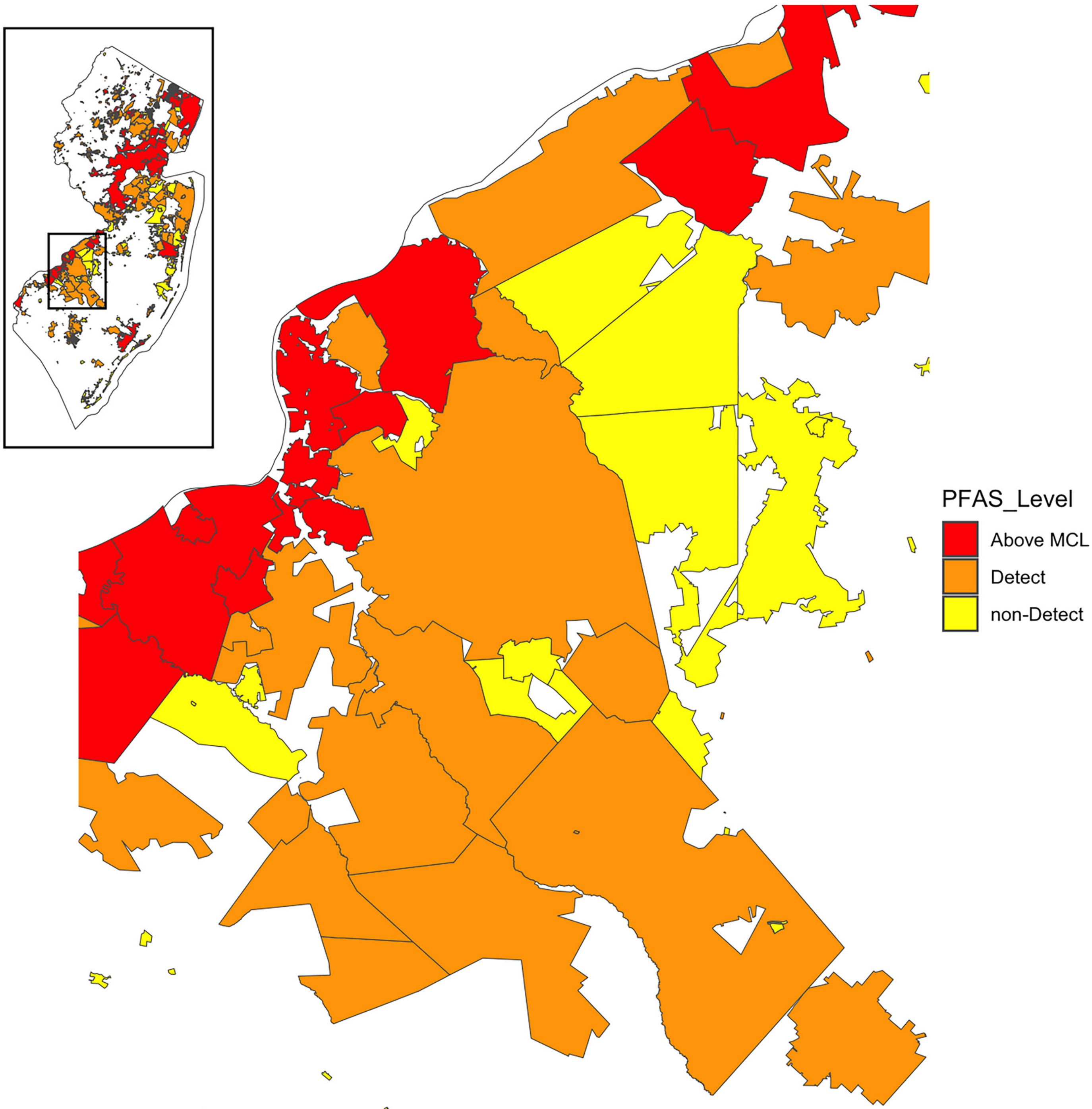

Figure 2. New Jersey CWSs ($n = 491$) by highest PFAS level reported to NJDEP. Figure 2 depicts community water system (CWS) service areas by the maximum reported PFAS levels from 2019 to 2021, zoomed into a portion of southwest New Jersey near Camden as an example. CWSs are shaded yellow (lightest) if the CWS never reported PFAS above minimum reporting levels (i.e., nondetect), orange if PFAS were detected above minimum reporting levels but below NJ maximum contaminant levels (MCLs), and red (darkest) if at least one sample within the CWS reported PFAS above one of the NJ MCLs (13 ng/L for PFNA, 13 ng/Lfor PFOA, or 14 ng/Lfor PFOS). Data for this figure are described in Table 1, column 2. Note: NJDEP, New Jersey Department of Environmental Protection; PFAS, per- and polyfluoroalkyl substances; PFNA, perfluorononanoic acid; PFOA, perfluorooctanoic acid; PFOS, perfluorooctane sulfonate.

Table 3. Community water systems—difference in mean attributes by OBC status (2019–2021).

	Any OBC					POC >30%			
	All	Yes	No	*p*-Stat	*p*-Value	Yes	No	*t*-Stat	*p*-Value
Total no.	491	233	258	—	—	188	303	—	—
Population served	16,177	31,940	1,942	−5.845	<0.001	37,733	2,803	−6.692	<0.001
Groundwater	0.796	0.644	0.934	8.533	<0.001	0.596	0.921	9.432	<0.001
Surface water	0.0468	0.0944	0.00388	−4.844	<0.001	0.112	0.0066	−5.510	<0.001
Purchased water	0.145	0.245	0.0543	−6.208	<0.001	0.271	0.066	−6.543	<0.001
Water treatment	0.919	0.979	0.864	−4.713	<0.001	0.984	0.878	−4.248	<0.001
PFAS detected	0.627	0.695	0.566	−2.982	0.003	0.734	0.561	−3.905	<0.001
Above NJ MCL	0.143	0.176	0.112	−2.016	0.044	0.197	0.109	−2.723	0.007
Above EPA proposed MCL	0.485	0.562	0.415	−3.295	0.001	0.617	0.403	−4.715	<0.001

Note: A community water system (CWS) serves an overburdened community (OBC) if at least one census block group within its service area is characterized as an OBC according to thresholds determined by New Jersey Department of Environmental Protection (NJDEP). Each *t*-statistic and *p*-value reflects results of difference-in-means tests between *a*) CWSs that serve an OBC vs. CWSs that do not serve an OBC, and *b*) CWSs that serve communities with more than 30% people of color (POC) vs. CWSs that do not serve communities with more than 30% people of color. Results for CWSs that serve communities with more than 30% low-income households or more than 40% households with limited English proficiency are reported in Table S8. —, no data.

Figure 2 depicts a map of maximum PFAS detections for each CWS in any quarter in 2019–2021 reported to NJDEP, reflecting significant heterogeneity in exposure to PFAS in drinking water across the state. Maximum detection levels for each CWS are displayed as "Above MCL," indicating that either PFNA, PFOA, and/or PFOS exceeded one of the NJ MCLs described above, "Detect" if any PFAS was detected above laboratory MRLs, or "Nondetect" if no PFAS were detected above MRLs within the CWS (Figure 2).

Table 3 presents CWS level summary statistics and difference in mean estimates of PFAS detections and additional water system characteristics by whether or not the CWS serves an OBC as defined by NJDEP. Statistics are reported based on whether the CWS serves a census block group meeting the NJDEP criteria of an OBC (more than 40% people of color, more than 35% low-income households, or more than 40% households with limited English proficiency) (Table 3).

CWSs serving an OBC were significantly more likely to serve a larger population (average population served = 31,940 for CWSs serving an OBC compared to 1,942 for CWSs not serving an OBC, $p<0.001$), more likely to be reliant on surface water compared to CWSs not serving an OBC (9.4% of CWSs serving an OBC compared to 0.4% of CWSs not serving an OBC, $p<0.001$), and significantly less likely to be reliant on groundwater (64% of CWSs serving an OBC compared to 93% of CWSs not serving an OBC, $p<0.001$). A total of 69.5% of CWSs serving an OBC had PFAS detections, compared to 56.6% of CWSs not serving OBCs ($p=0.003$), and OBC-serving CWSs were significantly more likely to be above NJ MCLs ($p=0.044$). Among block groups with more than 40% people of color, 73.4% of CWSs had PFAS detections and 19.7% of CWSs had PFAS detections above New Jersey's MCLs, compared to overall detection rates for CWSs not serving a block group with more than 40% people of color of 56.1% and 10.9%, respectively ($p<0.001$, $p=0.007$). Shown in Table S8, this pattern also holds for CWSs serving communities with a higher proportion of households with limited English proficiency. CWSs serving communities with a higher proportion of low-income households were more likely to have PFAS detections but not statistically more likely to exceed NJ MCLs. A comparable analysis based on UCMR3 testing (2013–2015) is reported in Table S9.

Having investigated differential PFAS detections at the CWS level, we further investigated whether certain demographic groups were differentially burdened with PFAS detections in public drinking water. Table 4 depicts statewide summary statistics of the demographics of the population served by CWSs whose public drinking water was tested for PFAS by NJDEP from 2019 to 2021. Eighty-four percent of the total population tested by NJDEP was served by CWSs that had PFAS detections, 72% were served by CWSs that had PFAS detections above the EPA's proposed MCLs, and 33% were served by CWSs that had PFAS detections above at least one NJ MCL. Ninety-two percent of the Hispanic population, 94% of the Black population, and 95% of the Asian population were served by CWSs that had PFAS detections, compared to 76% of the non-Hispanic white population.

Additionally, higher proportions of Asian, Hispanic, and Black populations were served by CWSs with PFAS detections above NJ MCLs and above EPA proposed MCLs compared to the non-Hispanic white population. Residents in low-income households were served by CWSs with slightly higher rates of PFAS detections compared to the overall population (87% vs. 84%) but experienced slightly lower rates of PFAS detections above NJ MCLs and EPA proposed MCLs. Residents in limited English proficient households experienced higher rates of both PFAS detections and detections above relevant thresholds compared to the overall population (Table 4). A comparable analysis based on UCMR3 testing (2013–2015) is reported in Table S10.

Table 5 reports estimates of the state population by water source (Table 5). Table 6 reports estimates of population demographics within CWSs excluded from NJDEP testing because of their reliance on purchased water and estimates of the population reliant on private wells. The population with CWSs reliant on purchased water is similar to the population within tested CWSs. The population reliant on private wells notably includes a larger proportion of white, non-Hispanic residents (Table 6).

Finally, to investigate trends in PFAS drinking water detections, we estimated the change in the likelihood of PFAS detection over the twelve quarters of NJDEP testing. Results are

Table 4. Summary statistics for NJ population within tested CWSs (2019–2021) ($n=491$).

	Proportion of tested population	PFAS detected	Above NJ MCL (4Qavg)	Above proposed EPA MCL
All	—	84%	33%	72%
White non-Hispanic	55.0%	76%	27%	67%
People of color	45.0%	93%	40%	79%
Hispanic	19.8%	92%	38%	78%
Black	13.3%	94%	34%	71%
Asian	9.2%	95%	52%	90%
Low-income	23.8%	87%	29%	71%
Limited English	6.8%	95%	40%	79%

Note: Table 4 depicts aggregate population estimates and PFAS detections for demographic groups within the service areas of community water systems (CWSs) in New Jersey that were tested for PFAS by New Jersey Department of Environmental Protection (NJDEP) (2019–2021). The percentages for PFAS detections represent the proportion of the tested population within each demographic group. —, no data; PFAS, per- and polyfluoroalkyl substances.

Table 5. Summary statistics for NJ population by water source.

Water source	Proportion of state population
CWS tested by NJDEP	77%
CWS not tested by NJDEP	10%
Non-CWS, private wells	13%

Note: Table 5 depicts aggregate population estimates for the New Jersey population by water source. CWS, community water system; NJDEP, New Jersey Department of Environmental Protection.

presented in Table S11. Systems were less likely to exceed NJDEP MCL's over time ($p < 0.01$), and systems that installed treatment were less likely to detect any PFAS ($p < 0.01$). Results are qualitatively similar for the logistic and linear regressions. We find a positive coefficient on the interaction term between trend and OBC, indicating there is a less pronounced decline in PFAS detections above NJDEP MCLs for OBC-serving CWSs compared to non-OBC-serving CWSs. However, this is statistically significant only in the logistic regression (column 2) and not significant in the linear regression (column 4). This suggests there is some evidence for less remediation for CWSs that serve OBCs compared to CWSs that serve wealthier and/or less diverse populations. We find overall decreases in PFAS concentrations were driven by declines in PFNA and PFOA, described in columns 5 and 6.

Discussion

In this study, we identified the extent of PFAS contamination in municipal drinking water in New Jersey, which adopted the United States' first PFAS MCL, and assessed how contamination is inequitably distributed. Across the state, a higher proportion of Black, Asian, and Hispanic residents receive public drinking water from CWSs with PFAS detections compared to the non-Hispanic white population. The population within households with limited English proficiency also saw higher rates of PFAS detection. Our study is consistent with recent research, including an "exploratory" study by the Government Accountability Office, which found that "disadvantaged communities" were more likely to receive PFAS-contaminated drinking water in New Jersey but less likely to receive PFAS-contaminated drinking water in Massachusetts.[53] We found mixed evidence that low-income populations are receiving PFAS-contaminated drinking water. While CWSs serving low-income block groups were more likely to have any PFAS detections or detections about EPA's proposed MCLs (Table S8), the percent of the low-income population receiving PFAS-contamination drinking water was not meaningfully higher than the percent overall (Table 4). Our results

Table 6. Summary statistics for NJ population outside of tested CWSs.

Demographic group	Proportion of population served by private wells	Proportion of population served by excluded CWSs[a]
White, non-Hispanic	75.20%	48.80%
People of color	24.80%	51.20%
Hispanic	10.10%	29.20%
Black	5.70%	9.60%
Asian	6.51%	9.70%
Low income	15.90%	21.30%
Limited English	2.31%	3.70%

Note: Table 6 depicts aggregate population estimates for demographic groups residing within areas served by private wells and areas served by community water systems (CWSs) excluded from NJDEP testing. NJDEP, New Jersey Department of Environmental Protection.
[a]This category includes 74 CWSs that use purchased water from other systems as their primary water source. These systems were not required by NJDEP to test their water for PFAS.

suggest considerable cause for concern about race- and ethnicity-based disparities in PFAS exposure, in addition to and distinct from disparities motivated by socioeconomic status.

Baden et al. found the choice of geographical scale and aggregation can influence environmental equity analysis.[54] Previous studies have often relied on demographic data at the county or zip code levels, which are generally much larger than the CWS service areas.[7,53,55,56] For example, Liddie et al.[12] assigned CWSs to hydrologic units rather than using precise CWS boundaries and used Census demographic data at the county level. By focusing on a single state with high-quality PFAS data and precise spatial data for CWS boundaries, we were able to use demographic data at the census block group level and aggregate up to the CWS service area, providing more precise representation of demographics at the CWS level.

Notably, the USEPA's proposed MCLs for PFOA and PFOS of 4 parts per trillion (ppt) are lower than the MCLs established by NJDEP,[44] and the USEPA's health-based maximum contaminant level goals (MCLG) are zero for PFOA and PFOS.[44] Thus, any detection of these contaminants above MRLs is potentially concerning.[57] Our trend analysis (Table S11) shows that rates of PFAS detections are decreasing over time, particularly in CWSs that have installed water treatment. We see larger disparities for detections above USEPA's lower proposed MCLs by race-ethnicity and limited English proficiency. The technical and economic justifications for USEPA's MCLs conclude that people of color and those with low income will see greater reductions in PFAS exposure under the proposed regulation compared to the non-Hispanic white population.[44] Our research suggests that disparities in PFAS exposure from drinking water exist and, therefore, that these proposed federal regulations could potentially reduce these disparities.

Limitations

Our study uses PFAS detections in finished water samples from CWSs that serve NJ households as a proxy for exposure to PFAS contamination. This is similar to studies that rely on SDWA violations or levels of other contaminants as a proxy for contamination, as researchers are often unable to directly measure PFAS exposure through drinking water consumption.[6–10,55,56,58,59] As a consequence of our approach, we are unable to interpret PFAS detections in drinking water as definite "exposure" to PFAS for several reasons.

First, water is sampled at specific locations including groundwater wells, surface water intakes, common headers, treatment plants, interconnections, and distribution systems. We used the sample representing delivered water (typically treated water, although untreated water is delivered by $\sim 8\%$ of CWSs). However, our data do not necessarily reflect delivered water at every tap within a CWS because some CWSs have multiple intakes or sample locations and additional blending can occur before delivery. Thus, concentrations for end users may be different from those at the tested source.

Second, we do not observe which households have point-of-use filters or if they rely on bottled rather than tap water for drinking water. Some (but not all) point-of-use filters have been shown to be effective at removing some or all PFAS,[60] and one study detected PFAS in 39% of bottled water samples,[61] suggesting that individual actions to reduce PFAS exposure may be limited in effectiveness.[62] Furthermore, we are unable to capture other sources of drinking water exposure, such as occupational, educational, or recreational points of drinking water consumption. Relatedly, we restrict our analysis to CWSs since we focus on the demographics of where people live, not necessarily where they spend other time such as at work or school. Schools, office buildings, and other nontransient noncommunity water systems were also tested for PFAS but are not included in this analysis.

Several methodological decisions impact our findings. Our analysis intersected demographic data with spatial boundaries of CWS service areas and estimated demographics of CWS populations. While this "areal apportionment method" is a widely used technique in spatial environmental justice analysis,[63–65] it requires an assumption that the population within each Census block group is uniformly distributed. Additionally, our results for "Any PFAS Detection" may be biased downward since detection values below MRLs are not observed. MRLs vary by method used and discretion of the laboratory technician; however, 94% of samples report MRLs between 1 and 2 ng/L. This data limitation may slightly underestimate the results for CWSs exceeding the USEPA's proposed MCLs for PFOA and PFOS since the proposed value is 4 ng/L. About 6% of samples in our data use an MRL of 5 ng/L, and an unknown number of those samples could be below the MRL but above the proposed MCL.

Our analysis does not include households reliant on private wells or CWSs reliant on water purchased from another CWS. Private wells are excluded from NJDEP MCL testing, reporting, and remediation mandates. Purchased water is tested within the system where it originates.

Finally, the trend analysis in this study misses any remediation that may have taken place prior to NJDEP testing in 2019. As mentioned above, NJDEP conducted the first statewide monitoring studies for PFAS in the US in 2006 and 2009.[66,67] Thus, our analysis refers only to the specified time periods and is unable to capture longer trends in PFAS levels in New Jersey CWS drinking water.

Conclusions

Our analysis suggests the need for increased monitoring and regulatory enforcement of PFAS and other environmental contaminants across the United States to help policymakers identify and address racial, ethnic, and socioeconomic disparities in pollution exposure. Disproportionate exposure to PFAS by people of color may lead these populations to experience higher rates of adverse health outcomes associated with PFAS exposure, further exacerbating existing inequalities. New Jersey makes an ideal case study for this analysis, not only because they were the first to implement an enforceable MCL and thus have high quality CWS-level data, but because NJDEP has been proactive in their regulatory efforts to address PFAS, as demonstrated in their nation-leading PFAS MCLs and efforts to hold polluters responsible for contamination, including multiple lawsuits against polluting companies.[68,69] With more and more states conducting PFAS testing and national testing conducted through the Fifth Unregulated Contaminant Monitoring Rule (UCMR5) in 2023–2025, future research should assess population exposure to PFAS detections in other states and nationally.

The major manufacturers of PFOA, PFOS, and PFNA agreed to phase out production by 2015.[70] However, global use of these chemicals in consumer and industrial products continues, and environmental contamination remains widespread due to their high resistance to degradation over time, bioaccumulation in food chains, and creation as production and degradation byproducts.[71] Furthermore, there remain thousands of other PFAS in use, along with the continual emergence of new PFAS formulations.[72,73] Other PFAS continue to be developed and used with minimal oversight[72] despite calls for action by scientists, activists, and state and federal governments to regulate the chemicals as a class.[74–76]

Researchers, policymakers, and CWSs face immense challenges to effectively protect consumers from PFAS in municipal drinking water, while maintaining water affordability.[77] Policymakers should work to better protect consumers of municipal drinking water from continued PFAS exposure through point-source reductions in PFAS emissions, MCLs for additional PFAS, and point-of-delivery testing of public drinking water as well as private well water. The EPA's proposal for MCLs for six PFAS concluded that the benefits of lower MCLs were significant and were likely greater than the predicted costs, suggesting that decision-makers should be prioritizing more protective PFAS regulations.[44] Previous research has found that policies that explicitly provide information about pollution, such as mandated environmental testing and reporting, can lead to reductions in total pollution[78] and furthermore can reduce disparities in pollution exposure.[79]

Our findings that PFAS detections in public drinking water are both widespread and inequitable support the need for more states and the US government to take a proactive role in order to gain fuller knowledge of the extent of PFAS contamination and its environmental justice ramifications. Continued litigation to identify and hold responsible polluters accountable for contamination, combined with legislation to require non-PFAS alternatives for consumer and industrial applications, will also be important, as water treatment and remediation efforts to address PFAS contamination in water supplies are costly, particularly for small and under-resourced CWSs.[77]

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