Disparities in exposure to per- and polyfluoroalkyl substances (PFAS) in drinking water: Evidence from New Jersey

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Abstract

Despite growing concerns regarding the widespread exposure and toxicity of per- and polyfluoroalkyl substances (PFAS), there are currently no federal PFAS drinking water standards in the United States. In the absence of a federal standard, multiple states have enacted their own regulatory levels for PFAS contamination. We assess the scope of PFAS contamination in public drinking water in New Jersey, one of the first states to conduct systematic testing for PFAS, using NJ community water system (CWS) testing data from 496 water systems in 2019-2021, along with earlier testing data of 169 water systems from the U.S. Environmental Protection Agency's (EPA) Unregulated Contaminant Monitoring Rule (UCMR3) conducted in 2013-2015. We also analyze the sociodemographic characteristics of the population living within affected CWS service areas using demographic data at the Census Block Group level to calculate statewide summary statistics of the population receiving PFAS-contaminated drinking water. We find that 63% of all CWSs tested by NJDEP have detections of PFAS chemicals in public drinking water, collectively serving 84% of NJ's population that receives water from CWSs. CWSs serving higher proportions of Black, Hispanic, and Asian populations have higher PFAS detections and higher exposures above state regulatory limits. We also find that PFAS detections in NJ have decreased over time, predominately due to

installations of PFAS-specific water treatment. These findings highlight the importance of PFAS remediation efforts for protecting environmental health and justice.

Synopsis: This study quantifies inequities in exposure to PFAS contamination in drinking water, which is important for the design of policies to address environmental justice.

Introduction

Despite growing public health concerns regarding the widespread exposure and toxicity of a broad class of chemicals called per- and polyfluoroalkyl substances (PFAS), little is known about whether PFAS exposure through drinking water is evenly distributed across the U.S. population. Previous research has documented correlations between socioeconomic status (SES) and PFAS exposure identified with biomonitoring data; however, results have been mixed.[1–3] No known quantitative studies investigate environmental justice concerns related to PFAS exposure by linking PFAS levels in municipally provided drinking water to resident demographics. Our analysis captures levels of PFAS in public drinking water sources for a comprehensive population, compared to previously conducted biomonitoring studies which typically include relatively small sample sizes and do not differentiate levels of PFAS for different racial/ethnic or SES subpopulations.[4]

While an estimated 200 million U.S. residents receive drinking water contaminated with PFAS,[5] there are currently no enforceable federal drinking water standards for PFAS contaminants in the United States.[6] In response to the absence of federal regulations, state-level action accelerated significantly since 2018 in a variety of regulatory, legislative, and non-regulatory forms, including the adoption of maximum contaminant levels (MCLs) for drinking water and groundwater.[7] In 2018, New Jersey (NJ) became the first U.S. state to impose an MCL for any PFAS with its initial MCL for perfluorononanoic acid (PFNA).[8] In 2019, the New Jersey Department of Environmental Protection (NJDEP) began requiring broad, statewide PFAS testing of municipal drinking water systems.[9] Thus, New Jersey provides an ideal case for exploring the extent of PFAS drinking water contamination, the

demographics of residents receiving drinking water from public water supplies, and trends in remediation over time.

In the current study, we assess the scope of PFAS contamination in public drinking water in New Jersey and analyze the sociodemographic characteristics of the exposed population using three data sources: community water system (CWS) testing data from NJDEP from 2019-2021, New Jersey sites from the Environmental Protection Agency's (EPA) nationwide testing of CWSs from 2013-2015 as part of the Third Unregulated Contaminant Monitoring Rule (UCMR3), and demographic data at the Census Block Group level from the 2018 American Community Survey. The study is representative of all CWSs in New Jersey, with the exception of systems serving less than 10,000 residents that are reliant entirely on water purchased from other CWSs. Given New Jersey's proactive stance on monitoring and regulating PFAS contamination, we also assess the progress the state has made in remediation of PFAS by identifying trends in PFAS levels in a subset of 128 CWSs tested in both EPA's UCMR3 and the NJDEP testing program in 2019-2021. We conclude with a brief discussion of certain remediation methods that have likely contributed to decreases in PFAS detections throughout the state.

Background

New Jersey has a history of reckoning with industrial pollution caused by a large manufacturing sector, and in recent decades has taken a proactive approach in testing and monitoring efforts to protect residents and hold industries responsible for contamination accountable. Notable legislation, the likes of which are relatively uncommon in other states, include the 1976 Spill Compensation and Control Act, the 2001 Private Well Testing Act, and a 2016 mandate requiring all schools to regularly monitor for lead in drinking water.[10–12] Foundational to development of the state MCLs for PFAS were the 1984 amendments to the NJ Safe Drinking Water Act, which required the state to develop its own MCLs for a list of contaminants and to consider emerging contaminants that occur at levels of concern in New

Jersey drinking water in the future.[13]

Decades of research has shown that environmental hazards, including exposure to toxic substances and unsafe drinking water, are disproportionately experienced according to race and ethnicity, SES, and other lines of marginalization.[14–18] However, little research has investigated environmental justice issues specifically related to PFAS, a critical gap. PFAS contamination is correlated with the presence of military, fire training bases, airports, and other industrial sites that are responsible for PFAS pollution.[19,20] Due to historic racial discrimination in housing laws and inequitable enforcement of environmental regulations, many industrial polluting facilities and other point sources of pollution are located proximal to communities with higher proportions of minority populations.[21–23]

While quantitative research specifically focused on drinking water quality and environmental justice is relatively sparse, several studies have documented disproportionate exposure to poor water quality among marginalized groups. The case of lead-contaminated drinking water in Flint, Michigan provides a notable example where Black, Indigenous, and People of Color (BIPOC) communities in the city were exposed to the highest lead levels compared to whiter neighborhoods.[24]

Several papers find correlations between CWS compliance with the Safe Drinking Water Act (SDWA) and the racial and/or ethnic composition of the service population. McDonald and Jones (2018) found that lower SES and BIPOC communities are more likely to be served by a water utility receiving drinking water violations, including utilities with repeated violations.[25] Switzer and Teodoro (2018) find that CWSs serving higher populations of Black and Hispanic populations have more SDWA violations. However, they find this positive association is attenuated as SES increases.[26] Allaire et al. (2018) found CWSs in rural areas and CWSs serving a higher proportion of low-income minority residents have a higher likelihood of total coliform violations.[27]

Studies focusing on California's San Joaquin Valley found that CWSs serving a higher proportion of Hispanic residents were more likely to have high nitrate levels[28] and high

arsenic levels,[28] and these disparities also persisted for CWSs serving a higher proportion of residents of lower SES. In a nationwide analysis, Schaider et al. (2019) found that Hispanic populations are disproportionately exposed to nitrate contamination in drinking water.[29] Nigra et al. (2020) finds smaller CWSs reliant on groundwater, located in the Southwest, and serving Hispanic communities were more likely to have elevated arsenic levels.

A proactive regulatory approach to address pollution exposure can reduce environmental inequities. Colmer et al. (2020) found that the Clean Air Act (CAA) substantially reduced, but did not eliminate, the pollution gap between the most polluted and least polluted census tracts. Because more BIPOC communities were out of attainment with CAA requirements when the act went into effect, the air quality improvements in these communities was more substantial than the improvements experienced in communities with larger white populations. However, relatively more polluted areas in 1981 remained relatively more polluted in 2016, while less polluted communities stayed relatively less polluted.[31]

Some research has documented correlations between SES and PFAS exposure identified with biomonitoring data, though results have been mixed. Some studies found positive correlations between income and education with PFAS,[1–3] while another found African American women had lower levels of PFAS in their blood compared with non-Hispanic white women.[32] Biomonitoring data from the Centers for Disease Control and Prevention's (CDC) National Health and Nutrition Examination Survey (NHANES) suggests that Asian Americans and non-Hispanic Black Americans have the highest levels of exposure to certain PFAS.[33] In particular, Asians had the highest exposure levels for PFNA and PFOS in all years from 2011-2018 and for PFOA from 2017-2018, while Black Americans had the second highest levels for PFNA in 2011-2012 and PFOS from 2013-2014.

Given historical evidence of disproportionate pollution exposure by race and ethnicity, there is reason to suspect PFAS contamination in municipal drinking water may also be inequitably experienced. Mandatory statewide testing in New Jersey provides an opportunity to examine the distribution of PFAS contamination in municipal water supplies by race,

ethnicity, and SES, and to identify trends in exposure over time.

Overview of PFAS

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 U.S.

There are over 9,000 PFAS in the large chemical class,[34] and the compounds are used in over 200 use categories across consumer and industrial applications.[35] Perfluorooctane sulfonate (PFOS) and perfluorooctanoic acid (PFOA) are the most known and well investigated, and were produced in large amounts for decades until the early 2000s. U.S. production of PFOS and related compounds ended in 2002, and facing mounting regulatory scrutiny, the major manufacturers of PFOA and other related long chain chemicals, including perfluorononanoic acid (PFNA), agreed to phase out production by 2015.[36] However, due to high resistance to degradation over time and bioaccumulation in food chains, environmental contamination of these chemicals remains widespread.[37]

Human exposure to certain PFAS has been linked to a variety of health effects, including kidney and testicular cancer, immune system hypersensitivity and suppression, endocrine disruption, and adverse reproductive outcomes including decreased fertility rates and lower birth weights.[38–44] Some PFAS used as replacements to phased-out compounds, such as PFOA and PFOS, have shorter half-lives in blood, but available data suggests that they remain bioaccumulative, persistent, highly mobile in the environment, and have similar toxicity concerns.[45–48] Some of these replacement compounds also degrade to terminal perfluoroalkyl acids. Additionally, emerging PFAS continue to be developed and used as alternatives to well-known PFAS with minimal oversight,[49] despite calls and action by scientists, activists, and state and federal governments to regulate the chemicals as a class.[50–52]

The U.S. Centers for Disease Control and Prevention estimates that 98% of U.S. residents

have detectable levels of PFAS in their blood.[53] Humans are exposed to PFAS through multiple exposure pathways, including the consumption of contaminated food and drinking water, the migration of PFAS from food packaging or cookware, other consumer exposures (products ranging from dental floss to clothing to recreational equipment), and occupational exposures.[54]

Among these innumerable possible exposure pathways, consuming contaminated water is of particular concern. A recent analysis estimated that 200 million U.S. residents receive drinking water contaminated with PFAS.[5] PFAS are nearly ubiquitous in surface water, 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.[55,56] Additionally, even relatively low levels in drinking water can offer a greater contribution to serum concentrations than other ubiquitous sources such as consumer products.[57]

While the U.S. EPA has the authority to set federal standards for drinking water contaminants, there are currently no enforceable federal drinking water standards for any PFAS.[58] In 2016, the EPA adopted a non-enforceable lifetime health advisory (HA) of 70 ng/L for PFOA, PFOS, or the sum of the two.[6] However, since this health advisory is not enforceable, CWSs nationwide are not required to routinely test for PFAS or to treat water found to be contaminated. In February 2021, the EPA issued a regulatory determination to list PFOA and PFOS under the Safe Drinking Water Act,[59] though actual promulgation of enforceable standards is likely still years away.

Several early studies conducted by NJDEP indicated the presence of widespread exposure to PFAS contamination in New Jersey CWSs. A 2006 report that PFOA was detected at two CWSs led NJDEP to conduct a study of 29 water samples from an additional 23 CWSs across the state with PFOA detected in 20 (69%) of the tested water samples.[60] A later study sampled 30 intakes from 29 New Jersey CWSs for PFOA, PFOS, and eight other

perfluoroalkyl acids (PFAAs).[61] At least one PFAS was detected at levels above 5 ng/L in 70% of the CWS samples, and multiple PFAS were detected in 43% of the samples.

From 2013-2015, the EPA tested a nationwide sample of public water systems as part of its third Unregulated Contaminant Monitoring Rule (UCMR3). The UCMR3 required testing for all large U.S. CWSs (serving >10,000 people) and a limited sample of smaller CWSs. The UCMR3 tested for six PFAS, but minimum reporting levels (MRLs) were relatively high (20 ng/L for PFNA, 20 ng/L for PFOA and 40 ng/L for PFOS). In UCMR3, PFAS were detected in 194 CWSs across the U.S. (about 4% of those tested) serving about 16.5 million people in 36 states.[20] In New Jersey, 169 CWSs were tested during UCMR3 and PFAS was detected in 26, representing a detection rate nearly four times higher than the national average.

In August 2017, following the UCMR3 study and internal analyses conducted by NJDEP documenting widespread PFAS in CWSs, NJDEP proposed amendments to the state Safe Drinking Water Act Rules that included establishing an MCL for PFNA of 13 ng/L. The PFNA MCL was adopted in September 2018,[9] and required mandatory testing for PFNA for 400 small CWSs reliant on groundwater and 700 non-transient non-community (NTNC) water systems starting in the first quarter of 2019. NTNC systems are non-residential CWSs that regularly serve the same population for at least six months out of the year, such as schools, office buildings, and hospitals. In the first quarter of 2020, 145 additional systems, including 118 large CWSs reliant on groundwater and 27 CWSs reliant on surface water, were required to begin monitoring for PFNA.

In June 2020, NJDEP adopted a PFOA MCL of 14 ng/L and a PFOS MCL of 13 ng/L.[9] All public community and NTNC water systems were required to begin monitoring for PFOA and PFOS within the first quarter of 2021, with the exception of water systems entirely reliant on purchased water. However, throughout 2019 and 2020 many systems voluntarily reported PFOA and PFOS early, as well as additional unregulated PFAS. Notably, water systems were advised by NJDEP to sample for and report results for PFOA and PFOS with their

required PFNA sampling to help offset sampling costs.

In June, 2020, PFNA, PFOA and PFOS were added to the New Jersey List of Hazardous Substances and will be subject to the Private Well Testing Act, which requires testing of private wells at the time of real estate transactions, beginning December 1, 2021.[62] However, while results from private wells must be reported to the state, they are not made public and therefore cannot be included in this analysis.

Materials and Methods

We assessed the scope of PFAS contamination in New Jersey, sociodemographic characteristics of the state's exposed population, and trends in PFAS contamination across multiple drinking water testing programs. We used quarterly PFAS data reported to NJDEP by CWSs from the first quarter of 2019 through the fourth quarter of 2021. These data are publicly available from New Jersey's Drinking Water Watch.[63] Data on the spatial boundaries of CWS service areas, primary water source, population served, and sample location type were obtained from NJDEP. Additionally we used PFAS data reported to the EPA as part of UCMR3 conducted in 2013-2015. To estimate the racial and ethnic characteristics of the population served by CWSs, we used census block group boundaries and data from the 2013-2018 American Community Survey. Analyses were completed using both RStudio (R version 4.0.4) and Stata 15.1.

As described above, the UCMR3 sampled all large CWSs across the U.S. as well as a representative sample of small CWSs and NTNC water systems for six PFAS including PFNA, PFOA and PFOS. In New Jersey, this included testing of 169 CWSs and 6 NTNC water systems. The current study focuses solely on CWSs since we can only determine the racial and ethnic demographics of where people live, not necessarily where they spend other time.

NJDEP testing was required once the state adopted MCLs for PFNA (in 2018) and PFOA

and PFOS (in 2020). In the first quarter of 2019, all CWSs using a groundwater source(s) serving a population 10,000 or less and all public NTNC water systems were required to begin monitoring for PFNA. In the first quarter of 2020, all public CWSs using a surface water source(s) and all public CWSs serving a population greater than 10,000 were required to begin monitoring for PFNA. By the end of 2020, NJDEP had required PFAS testing for nearly all CWSs across the state for PFNA, with the exception of those systems entirely reliant on purchased water since that water must be tested by the CWS where it originates. Additionally, voluntary reporting of PFOA, PFOS, and up to nine additional PFAS, including all six PFAS reported in UCMR3, was common because the analytic methods used to detect PFNA also detected these other PFAS and CWSs were encouraged to report all analytes to help offset sampling costs.[64] In 2019 and 2020 when only PFNA reporting was required, nearly all systems also reported PFOA and PFOS, and roughly half reported additional unregulated contaminants. 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 Table A1 in the Appendix.

We analyzed 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), *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), *Above UCMR3 MRL* (an indicator if at least one PFAS included in the UCMR3 exceeded the UCMR3 minimum reporting levels [20ng/L for PFNA, 20ng/L for PFOA, and 40ng/L for PFOS]) and indicators for *PFNA Detected*, *PFOA Detected* or *PFOS Detected* above NJDEP minimum reporting levels (generally 2ng/L), and detections for individual exceedances of NJ MCLs (*PFNA >13ng/L*, *PFOA >14ng/L* and *PFOS >13ng/L*. We also estimated whether PFAS exposure varied for systems that primarily rely on surface water versus those primarily reliant on groundwater.

To calculate exceedances of the NJ MCL, we used the maximum four quarter rolling

average within a sample location for each CWS. We excluded "raw" water samples when treated samples were available for the same CWS because our analysis is intended to reflect "finished" water which is delivered to consumers. However, it is important to note that some small CWSs do not have water treatment and thus deliver "raw" water. NJDEP minimum reporting levels (MRLs) (below which "non-detect" rather than a number is recorded) vary based on laboratory methods and capabilities, but more than 90% of samples report non-detect at 2 ng/L or lower. The remaining CWSs report non-detect below 5 ng/L. As mentioned above, the minimum reporting levels reported in UCMR3 were set at 20 ng/L for PFNA, 20 ng/L for PFOA, and 40 ng/L for PFOS, higher than any of NJ's MCLs for these compounds.

Using the maximum four quarter average PFAS levels for each CWS approximates CWSs in violation of the NJ MCLs. MCL violations are based on the rolling annual average of four quarterly monitoring results, and CWSs are allowed up to one year to address violations. The PFOA and PFOS data submitted as part of PFNA MCL monitoring before the PFOA and PFOS MCLs were adopted could not have led to required actions to address PFOA and/or PFOS contamination, since regulations were not yet enacted.[64] However, testing submitted before enforcement can be used to reduce the frequency of testing from quarterly to annual testing and eventually to testing once every three years, if PFAS levels are consistently below MCLs.

To identify sociodemographic characteristics associated with receiving PFAS in their municipally-provided drinking water, we used census block group data from the 2013-2018 American Community Survey and associated 2018 shapefiles of census block groups. We included race and ethnicity variables capturing the proportion of the population that was non-Hispanic white, Hispanic, Black and Asian. To capture SES, we included the proportion of the population with household income categorized as below poverty. We intersected the spatial boundaries of the CWS service areas, available from NJDEP, with the census block group boundaries to approximate the demographics of the CWS service area. For each

demographic group of interest, we estimated the relative proportions of the total population for each group that reside within the spatial boundaries of a CWS service area. We then used this proportion scaled by the population served for each CWS to estimate the demographic characteristics of the population served by each CWS. We used these population estimates to estimate the proportion of each racial and ethnic group that received municipal drinking water that met criteria for PFAS indicators described above. This method requires an assumption that population demographics are uniform within a census block group. We elected to use census block groups, since this is the smallest geographical unit for which demographic data are publicly available.

To analyze how PFAS contamination in CWSs has changed over time, we estimated changes in PFAS levels from the EPA's UCMR3 testing in 2013-2015 to the most recent NJDEP test in 2019-2021. The UCMR3 testing in New Jersey included 1,442 total samples from 169 CWSs. As mentioned above, UCMR3 used much higher MRLs than NJDEP, making it difficult to draw a direct comparison. Acknowledging these limitations, we estimated the change in the likelihood of detection above the higher UCMR3 MRLs using just the subset of 484 unique sample locations from 127 CWSs that were included as part of UCMR3 and NJDEP testing. We focus on matched sample locations to ensure we are comparing the same sites that were sampled during UCMR3 and re-sampled during NJDEP. This excludes CWSs that were not re-sampled in NJDEP because they rely entirely on purchased water, as well as CWSs that sampled at different locations across the two testing programs. We estimated a linear regression including sample location fixed effects to control for all time invariant differences across sample locations. We also look specifically at average changes in reported PFAS levels for CWSs that have installed, or are actively installing, PFAS-specific water treatment. These data were obtained by data request from NJDEP, and include 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 we use these data to indicate CWSs that are actively working to remediate PFAS in drinking

water.

Lastly, to understand trends in PFAS levels since New Jersey initiated mandatory testing for some PFAS, we estimated a linear trend in PFAS detections and levels using the twelve quarters of data reported to NJDEP from 2019-2021. Using the sample level data, we estimated a linear time trend with sample location fixed effects to estimate the average within sample location trend over time. It is important to note that these trend analyses miss any remediation that took place prior to UCMR3 and NJDEP testing. As mentioned above, NJDEP conducted the first statewide monitoring studies for PFAS in the US in 2006 and 2009.[60,61] Thus our analysis refers only to the specified time periods and may mis-estimate longer trends in PFAS levels in New Jersey CWS water.

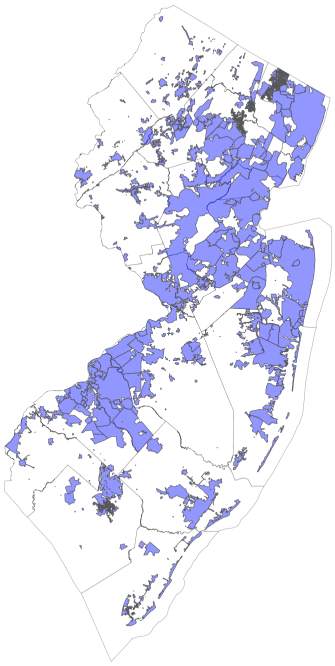
Results and Discussion

Figure 1 depicts a map of CWS boundaries across the state. Areas outside of the CWS boundaries are generally rural areas reliant on private wells for drinking water, rather than CWSs. Private wells are not included in our analysis since all private well owners are not required to test for PFAS by NJ MCLs.

Table 1 reports the summary statistics of PFAS testing in UCMR3 (Panel a) and NJDEP (Panel b). 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 detections and maximum four quarter average sample values of delivered water for each CWS. Column (3) reports estimates of population exposure to PFAS detected in municipal drinking water from both the UCMR3 (Panel a) and NJDEP (Panel b). 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 UCMR3, 169 New Jersey CWSs serving an estimated population of 8.1 million resi-

Figure 1: NJ PWS Service Area Boundaries



dents were tested for PFAS, with 1,442 total samples (Table 1, Panel a). At least one PFAS analyte was detected in 15% of systems, representing 22% of the population served by tested CWS. Of all CWSs tested for PFAS from 2019-2021, 63% detected positive amounts of at least one PFAS analyte (Table 1, Panel b). These systems provide water to 84% of the population served by tested water systems. Just 1.8% of systems detected PFNA above the NJ MCL of 13 ng/L, representing just over 1% of the population served by CWSs in the state. Notably, 8% of CWSs detected either PFOA or PFOS above NJ MCLs, representing 20% and 6% of the population served by tested CWS. Nearly 23% of New Jersey residents received drinking water with exceedances above NJ MCLs at some point from 2019-2021.

While the results in Table 1 show an increase in PFAS detections over time, the minimum reporting levels were much higher during UCMR3 testing. While 15% of CWSs serving 22% of the population served by CWWs exceeded UCMR3 MRLs during UCMR3 (2013-2015), just 9% of CWSs exceeded these same levels during the NJDEP testing (2019-2021), representing 19% of the population served. NJDEP tested considerably more water systems for

Table 1: Summary Statistics

a.) UCMR3 (2013-2015)

	(1) All Samples	(2) Unique CWS	(3) Population Served
n	1442	169	8,110,882
Groundwater	35.10%	40.83%	22.19%
Surface water	16.00%	12.43%	49.19%
Purchased surface water	48.00%	44.38%	26.93%
Water Treatment	96.00%	93.49%	99.13%
Above UCMR3 MRL	6.73%	15.38%	22.10%
PFNA >20ng/L Detected	0.49%	2.37%	0.89%
PFOA >20ng/L Detected	6.03%	11.24%	19.86%
PFOS >40ng/L Detected	0.83%	3.55%	11.53%

b.) NJDEP (2019-2021)

	(1) All Samples	(2) Unique CWS	(3) Population Served
n	7,853	496	7,943,458
Groundwater	70.7%	79.23%	28.19%
Surface Water	7.79%	5.24%	50.63%
Purchased Surface Water	20.8%	14.31%	19.52%
Water Treatment	92.3%	91.73%	99.94%
Any PFAS Detected	55.40%	63.10%	83.87%
Above NJ MCL (Max 4Q Avg)	7.46%	13.51%	22.66%
Above UCMR3 MRL	5.36%	9.48%	19.10%
PFNA Detected	8.65%	18.15%	31.11%
PFNA >13ng/L (Max 4Q Avg)	0.40%	1.81%	1.02%
PFOA Detected	52.20%	59.48%	81.13%
PFOA >14ng/L (Max 4Q Avg)	5.02%	8.47%	20.08%
PFOS Detected	43.40%	54.23%	76.34%
PFOS >13ng/L (Max 4Q Avg)	4.09%	8.47%	5.77%

Note: Data include PFAS samples for all CWSs tested in New Jersey. 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 detections and maximum four quarter average sample values of delivered water for each CWS. Column (3) reports estimates of population exposure to PFAS detected in municipal drinking water. Note the different reporting limits for UCMR3 (panel a.) compared to NJDEP (panel b.). "Above UCMR3 MRL" is comparable across datasets.

PFAS than were included in UCMR3, including many small CWSs excluded from UCMR3. However, the population size tested was much larger in UCMR3 (Table 1, column (3). Despite testing more water systems, the overall population served by CWSs tested by NJDEP is smaller than the overall population tested under UCMR3. This reflects the omission of 24 (including several large) CWSs from NJDEP testing which are entirely served by purchased water and therefore were not required to be tested for PFAS. See Table A1 in the Appendix for a complete list of CWSs and indicators for whether they were sampled for PFAS in either UCMR3 and/or by NJDEP.

Table 2 reports PFAS detections by primary water source distinguished between systems reliant on groundwater versus surface water. Analogous to Table 1, Panel a presents UCMR3 detections and Panel b presents NJDEP detections. While there are more CWSs primarily sourced from groundwater, surface water is the primary water source for most large CWSs in New Jersey, so the majority of the population receives drinking water from surface water sources. The UCMR3 primarily focused on large water systems, so there are more tested surface water systems than tested groundwater systems. Roughly 23% of tested surface water systems had reported PFAS detections, while just 6% of groundwater systems had reported PFAS detections during UCMR3.

Compared to UCMR3 testing, the NJDEP testing included many more small CWSs and many more CWSs reliant on groundwater. However, CWSs who exclusively purchase water were excluded from testing. During the NJDEP testing, 85% of CWSs reliant on surface water and 57% of CWSs reliant on groundwater have detected PFAS, representing 95% and 54% of the populations served, respectively. 18% of CWSs reliant on surface water and 7% reliant on groundwater had exceedances above at least one NJ MCL, predominantly driven by PFOA. Thus, surface water sources were more likely to have detectable levels of PFAS, though groundwater sources were also fairly commonly found to have elevated levels of PFAS.

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 across the

Table 2: Summary Statistics by Primary Water Source

a.) UCMR3 (2013-2015)

	Groundwater		**Surface Water**	
	(1)	(2)	(3)	(4)
	Unique CWS	Population	Unique CWS	Population
n	69	1,799,762	96	6,173,525
Above UCMR3 MRL	5.80%	5.24%	22.92%	27.51%
PFNA >20ng/L Detected	1.45%	0.69%	3.13%	0.97%
PFOA >20ng/L Detected	2.90%	1.88%	17.71%	25.54%
PFOS >40ng/L Detected	1.45%	2.67%	5.21%	14.37%

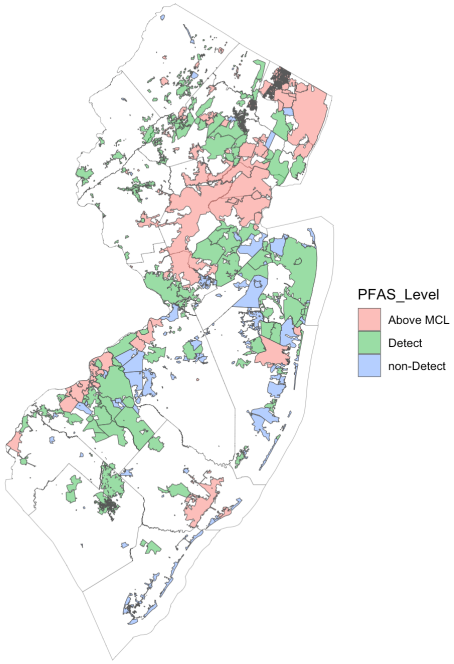
b.) NJDEP (2019-2021)

	Groundwater		**Surface Water**	
	(1)	(2)	(3)	(4)
	Unique CWS	Population	Unique CWS	Population
n	393	2,238,915	97	5,572,264
Any PFAS Detected	57.25%	54.49%	84.54%	95.29%
Above NJ MCL (Max 4Q Avg)	11.45%	10.08%	22.68%	28.26%
Above UCMR3 MRL	7.38%	10.62%	17.53%	22.96%
PFNA Detected	13.49%	22.50%	35.05%	33.43%
PFNA >13ng/L (Max 4Q Avg)	1.27%	1.53%	4.12%	0.84%
PFOA Detected	54.20%	51.49%	78.35%	92.59%
PFOA >14ng/L (Max 4Q Avg)	6.87%	6.39%	15.46%	26.06%
PFOS Detected	49.36%	50.97%	72.16%	85.98%
PFOS >13ng/L (Max 4Q Avg)	8.65%	5.22%	8.25%	6.12%

Note: Data include PFAS samples for all tested CWSs in New Jersey. Columns (1) and (3) aggregate data to the CWS level, reflecting detections and maximum four quarter 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. Note the different reporting limits for UCMR3 (panel a.) compared to NJDEP (panel b.). "Above UCMR3 MRL" is comparable across datasets. CWSs who purchase groundwater or surface water are also included in the above table. However, as noted earlier systems entirely reliant on purchased water were not required to test for PFAS under NJDEP.

state. Maximum detection levels for each CWS are displayed as "Above MCL" indicating either PFNA, PFOA or PFOS exceeds one of the NJ MCLs described above, "Detect" if any PFAS is detected, or "Non-detect."

Figure 2: NJ PWS by Highest PFAS Level Reported to NJDEP



Note: The above figure depicts the maximum sample value (restricted to treated samples when available) for each unique PWS during NJDEP testing from 2019-2020.

Table 3 depicts the estimated population of certain racial and ethnic groups and the population reporting income below the federal poverty line who received PFAS in municipal drinking water from results reported under UCMR3 (Panel a) and NJDEP (Panel b). Results from UCMR3 finds that the Black and Asian populations in New Jersey are more likely to be exposed to PFAS in municipal drinking water compared to non-Hispanic white and Hispanic populations.

Results from NJDEP testing find that in communities served by CWSs, Hispanic, Black and Asian populations are all more likely to receive municipal drinking water with detectable levels of PFAS, compared to the non-Hispanic white population. Notably, nearly 92% of

Black and 95% of Asian populations have detectable levels of PFAS in their municipal drinking water, compared to 75% of the non-Hispanic white population. Additionally, higher proportions of Asian, Hispanic and Black populations receive drinking water with PFOA and PFOS levels above NJ MCLs. PFNA detections are much lower across the UCMR3 and NJDEP samples, and there is no evidence of disproportionate exposure by race.

Table 3: Demographics of Exposed Population

a.) UCMR3 (2013-2015)

	(1) **All**	(2) **White, non-Hispanic**	(3) **Hispanic**	(4) **Black**	(5) **Asian**	(6) **Below Poverty**
Proportion of Tested Population		53.88%	21.43%	13.66%	9.69%	11.70%
Above UCMR3 MRL	22.10%	19.57%	16.73%	24.45%	31.00%	17.87%
PFNA >20ng/L	0.89%	1.30%	0.35%	0.97%	0.27%	0.77%
PFOA >20ng/L	19.86%	16.46%	15.82%	22.83%	28.14%	16.52%
PFOS >40ng/L	11.53%	11.17%	10.35%	15.39%	18.53%	11.86%

b.) NJDEP (2019-2021)

	(1) **All**	(2) **White, non-Hispanic**	(3) **Hispanic**	(4) **Black**	(5) **Asian**	(6) **Below Poverty**
Proportion of Tested Population		56.44%	19.58%	13.42%	9.19%	11.56%
Any PFAS Detected	83.87%	75.12%	91.67%	93.14%	94.53%	86.11%
Above NJ MCL (Max 4Q Avg)	22.66%	18.53%	19.24%	27.14%	32.79%	18.49%
Above UCMR3 MRL	19.10%	17.79%	18.90%	24.51%	32.16%	18.47%
PFNA Detected	31.11%	34.73%	27.19%	30.23%	39.16%	25.44%
PFNA >13ng/L (Max 4Q Avg)	1.02%	1.45%	0.48%	0.91%	0.43%	1.05%
PFOA Detected	81.13%	71.26%	90.32%	91.04%	92.81%	84.28%
PFOA >14ng/L (Max 4Q Avg)	20.08%	15.71%	17.25%	22.60%	31.09%	16.19%
PFOS Detected	76.34%	69.09%	82.14%	76.01%	90.01%	73.98%
PFOS >13ng/L (Max 4Q Avg)	5.77%	4.91%	6.44%	9.73%	6.51%	9.43%

Note: The above table depicts aggregate population estimates for demographic groups residing within the service areas of CWSs in New Jersey that were tested for PFAS in UCMR3 (panel a.) or NJDEP (panel b.).

Across both UCMR3 and NJDEP testing, the population below poverty has similar rates of PFAS detection in municipal drinking water as the overall population, and slightly lower rates of detection above NJ MCLs or UCMR3 MRLs.

Table 4 panel (a) reports results from a linear regression, described in equation (1), estimating the change in the likelihood of PFAS detection ($Above\_UCMR3_{it}$) from UCMR3 to the most recent test reported to NJDEP ($NJDEP_t$). γ_i denotes a sample location fixed ef-

fect. The analysis includes all CWS sample locations tested during both the EPA's UCMR3 in 2013-2015 and NJDEP's more recent testing (n=484). Resulting coefficients can be interpreted as the average change in likelihood of PFAS detection above UCMR3 MRLs from UCMR3 to the most recent sample reported. Sample location fixed effects are included in all specifications, to control for all characteristics of CWSs that are constant over time, such as system size, primary water source, location, and demographics of population served. Thus, results reflect the average of within-sample-location changes over time. For all sample locations reporting in both UCMR3 and NJDEP, samples were 1.87 percentage points less likely to find PFAS above UCMR3 MRLs (b = -0.018698, p-value <0.1).

$$Above\_UCMR3_{it} = \beta_0 + \beta_1 NJDEP_t + \gamma_i + \epsilon_{it} \tag{1}$$

Panel (b) reports results for this same subset of CWS sample locations with an additional indicator for whether the CWS applied for a permit to install PFAS-specific water treatment, $PFAS_Treatment_{it}$ described in equation (2). For CWSs that applied for PFAS-specific treatment, the most recent NJDEP sample was 9.5 percentage points less likely to exceed UCMR3 MRLs (b= -0.0947, p-value <0.05). This effect was primarily driven by decreased likelihood of detection for PFOA (b=-0.894, p-value<0.05). The coefficient on $NJDEP$, representing the average decline for all repeated sample locations, was not statistically significant. These results suggest active remediation efforts, such as installing new PFAS-specific water treatment, is leading to decreases in PFAS detections in CWSs in New Jersey.

$$Above\_UCMR3_{it} = \beta_0 + \beta_1 NJDEP_t + \beta_2 PFAS\_Treatment_{it} + \gamma_i + \epsilon_{it} \tag{2}$$

Table 5 presents results of a linear trend analysis, described in equations (3)-(5), for PFAS levels reported to NJDEP since 2019. Some CWSs did not begin reporting until 2020, and CWSs with four consecutive quarters of PFAS below NJ MCLs can switch to annual

Table 4: Change from UCMR (2013-2015) to NJDEP (2019-2021)

I(Detect) above UCMR3 Detection Levels

a.) All Repeated Samples

	(1) UCMR Detect b/se	(2) PFNA >20ng/L b/se	(3) PFOA >20ng/L b/se	(4) PFOS >40ng/L b/se
NJDEP	-.0186*	-.00413	-.0124	-.0062*
	(.0107)	(.00292)	(.0101)	(.00357)
R^2	0.006	0.004	0.003	0.006
Observations	968	968	968	968

b.) With Indicators for PFAS Treatment

	(1) UCMR Detect b/se	(2) PFNA >20ng/L b/se	(3) PFOA >20ng/L b/se	(4) PFOS >40ng/L b/se
NJDEP	3.57e-18	-.00257	.00514	-.00257
	(.00815)	(.00257)	(.00728)	(.00257)
PFAS Treatment	-.0947**	-.00796	-.0894**	-.0185
	(.0432)	(.0108)	(.0419)	(.015)
R^2	0.032	0.007	0.028	0.015
Observations	968	968	968	968

* p-value<0.1, ** p-value<0.05, *** p-value<0.01
Note: Restricted to sample locations tested by both UCMR3 and NJDEP. Some Heteroskedastic-robust standard errors are reported.

testing and reporting, so our data represents an unbalanced panel with up to twelve quarters of reporting for each sample location. Panel (a) reports results for the likelihood of a detection of above NJ MCLs ($Above\_NJ\_MCL_{it}$)), while Panel (b) reports results for the linear change in PFAS levels (Sum_PFAS_{it}) (reported in ng/L), described in equations (3) and (4), respectively. Panel (c) reports results for the linear change in PFAS levels for CWSs who have installed, or are in the process of installing, PFAS-specific water treatment ($PFAS\_Treatment_{it}$), described in equation (5). Again, sample location fixed effects, denoted $gamma_i$ are included in all specifications, so results reflect the average of within-sample-location trends over time.

$$Above\_NJ\_MCL_{it} = \beta_0 + \beta_1 Quarter_t + \gamma_i + \epsilon_{it} \quad (3)$$

MCL exceedances for PFAS levels in New Jersey CWSs exhibited a statistically significant downward trend over time (b=-0.0035, p-value <0.01), largely driven by reductions in PFOA and PFOS MCLs (Table 5, Panel a). In each subsequent quarter of testing, a sample at a given location is 0.4 percentage points less likely to report PFAS above at least one of New Jersey's established MCLs. We also find overall statistically significant declines in PFAS levels across the twelve quarters of NJDEP data (Table 5, panel b), specifically for PFNA concentrations (-0.026 ng/L per quarter), and PFOA concentrations (-0.062 ng/L per quarter).

$$Sum\_PFAS_{it} = \beta_0 + \beta_1 Quarter_t + \gamma_i + \epsilon_{it} \quad (4)$$

In Table 5, panel c, we add an interaction term to separately estimate the trend for locations within CWSs that have applied for permits for PFAS-specific treatment compared to the overall trend for all sample locations. For locations that have applied for treatment permits, we find larger statistically significant declines in PFNA concentrations (-0.97 ng/L per quarter) and PFOA concentrations (-0.145 ng/L per quarter). Notably, when estimating the different trend for CWSs that have applied for treatment permits, the average trend for all sample locations was not statistically significant.

$$Sum\_PFAS_{it} = \beta_0 + \beta_1 Quarter_t + \beta_2 PFAS\_Treatment_{it} + \gamma_i + \epsilon_{it} \quad (5)$$

The statistically significant decreases in measured PFAS levels over time in CWSs identified in our trend analysis are particularly notable for PFOA, both since UCMR3 and since the beginning of NJDEP testing in the first quarter of 2019. These decreases appear primarily driven by installations of water treatment technologies designed to filter out PFAS from delivered drinking water. Effective technologies include reverse osmosis, granular activated

carbon (GAC), powdered activated carbon (PAC), and ion exchange filtration systems.[65,66] However, reductions could also be from CWSs increasing blending of contaminated water with cleaner water sources, removing certain wells or surface water intakes from service, or switching to alternative water sources.[64] With the start of enforcement of the recently passed MCLs for PFOA and PFOS enforceable starting in the first quarter of 2021,[8] we expect to see continued decreases in the presence of these contaminants in municipal drinking water.

Summary and Future Directions

In this study, we identified the scope of PFAS contamination in municipal drinking water in New Jersey and how contamination has evolved in recent years. Results reveal substantial and widespread detections of PFAS in public drinking water. Over 80% of New Jersey residents residing within CWS service areas have likely received drinking water with detectable PFAS levels, and 22% live within CWS service areas where water samples have exceeded at least one of the state's MCLs for PFNA, PFOA, or PFOS. These values are higher for populations receiving public drinking water from surface water sources compared to groundwater sources.

We also estimated the sociodemographics of populations residing in CWS service areas using aggregated census block group data, and found that a higher proportion of Black, Asian, and Hispanic populations receive public drinking water with elevated PFAS compared to the non-Hispanic white population. Our study does not find that populations below the federal poverty line had higher PFAS levels in public drinking water compared to the overall population. This suggests serious cause for concern about race- and ethnicity-based disparities in PFAS exposure, distinct from disparities motivated by SES. However, since our analysis is primarily descriptive, we are unable to address confounding factors such as the CWS size or urban/rural residence. We are also unable to analyze PFAS exposure through drinking water consumption, since we measure only the delivery of drinking water by CWSs.

Our analysis suggests the need for increased monitoring and regulatory enforcement of

PFAS and other environmental contaminants across the U.S. to help policymakers address racial and ethnic disparities in pollution exposure. Disproportionate exposure by disadvantaged racial and ethnic groups may lead these populations to experience higher rates of adverse health outcomes linked to PFAS exposure, further exacerbating existing inequalities.

NJDEP has been relatively proactive in their regulatory efforts to address PFAS, as demonstrated in their nation-leading MCLs on three PFAS, required PFAS testing and remediation for all community CWSs, and efforts to hold polluters responsible for contamination, including multiple lawsuits against polluting companies. However, there remain thousands of unregulated PFAS in use, along with the continual emergence of new PFAS formulations.[49,67]

Researchers, policymakers, and CWSs face immense challenges to effectively protect consumers from PFAS in municipal drinking water, while maintaining water affordability. Policymakers should work to better protect consumers of municipal drinking water from continued PFAS exposure through MCLs for additional PFAS and point-source reductions in PFAS emissions. One strength of our analysis is that NJDEP testing has much lower reporting limits than UCMR3, providing a more accurate estimate of population exposure than was previously available with UCMR3 data.

Our findings that PFAS detections in public drinking water are both widespread and inequitable support the need for more states to take such a proactive role in order to gain fuller knowledge of the extent of PFAS contamination and its environmental justice ramifications. In October 2021, the U.S. EPA announced its "PFAS Strategic Roadmap" which includes plans to establish national primary drinking water regulation for PFOA and PFOS that would set enforceable limits and require monitoring of public water supplies, while evaluating additional PFAS and groups of PFAS.[68] Given the disproportionate exposure patterns identified in New Jersey in this research, national remediation efforts may need to focus on water systems serving higher proportions of BIPOC populations. Continued litigation to identify and hold responsible polluters accountable for contamination, combined with efforts to require non-PFAS alternatives for consumer 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.[69] While phasing out contaminants from industrial production and consumer use is needed, the persistence of PFAS as a class underscores the need for equitable water treatment and remediation efforts to protect consumers and address demographic disparities in exposure.

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Table 5: ALL NJDEP Samples (2019-2021)

a.) I(Detect) above NJDEP MCLs

	(1) Above NJ MCL b/se	(2) PFNA >13ng/L b/se	(3) PFOA >14ng/L b/se	(4) PFOS >13ng/L b/se
Quarter	-.00353***	-.000618	-.00387***	-.00376***
	(.00108)	(.0005)	(.000835)	(.000921)
R^2	0.004	0.001	0.007	0.008
Observations	7,853	7,844	7,610	7,600

b.) Numerical Value (ng/L)

	(1) Sum PFAS (ng/L) b/se	(2) PFNA (ng/L) b/se	(3) PFOA (ng/L) b/se	(4) PFOS (ng/L) b/se
Quarter	-.11	-.0261**	-.0621***	-.0535
	(.0795)	(.0114)	(.0224)	(.0393)
R^2	0.001	0.003	0.005	0.001
Observations	7,853	7,844	7,610	7,600

c.) Numerical Value (ng/L) with Indicators for Treatment

	(1) Sum PFAS (ng/L) b/se	(2) PFNA (ng/L) b/se	(3) PFOA (ng/L) b/se	(4) PFOS (ng/L) b/se
Quarter	-.0876	-.00727	-.0349	-.0301
	(.0736)	(.00693)	(.0247)	(.0388)
Treatment×Quarter	-.114	-.0974*	-.145**	-.125
	(.283)	(.0514)	(.0576)	(.131)
R^2	0.001	0.011	0.009	0.003
Observations	7,853	7,844	7,610	7,600

* p-value<0.1, ** p-value<0.05, *** p-value<0.01
Note: Time represents a quarterly linear trend. Heteroskedastic robust standard errors are reported. Sample location fixed effects are included in all specifications.

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Graphical TOC Entry