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Rose Hefferon April 21, 2022

Nationwide Inequalities in Public Drinking Water Fluoride Exposure, 2006-2011

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Abstract

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Background: Fluoride has been added to public drinking water systems in the US for decades to prevent and reduce dental disease, and recent epidemiologic evidence suggests fluoride exposure may be associated with adverse child neurodevelopment. Yet nationwide estimates of public water fluoride exposure are not currently available. Our objective was to estimate public water fluoride exposure across the US and identify potential exposure inequalities across geographic or sociodemographic groups in geospatial regression models.

Methods: We generated CWS-level and weighted county-level public water fluoride exposure estimates across the US using 256,237 routine compliance monitoring records for fluoride from 32,495 community water systems (CWSs). Data was collected from the Environmental Protection Agency's (EPA) Third Six Year Review of Contaminant Occurrence dataset, 2006-2011. We compared fluoride distributions and the percent of CWSs exceeding EPA's maximum contaminant level (MCL) and the World Health Organization's Guideline for drinking water quality (WHO GDWQ) across major subgroups served by CWSs including region, population size served, and community sociodemographic characteristics. We further evaluated geometric mean ratios (GMRs) of CWS fluoride in spatial lag regression models per 10% increase in the proportion of residents belonging to a given racial/ethnic subgroup.

Results: A total of 4.5% of CWSs had mean 2006-2011 fluoride concentrations that exceeded WHO's GDWQ of 1,500 µg/L. Arithmetic mean, 75th, and 95th percentile contaminant concentrations were greatest in CWSs reliant on groundwater, CWSs in the Southwest, and CWSs serving Semi-Urban, Hispanic communities. In fully adjusted spatial lag models, the GMR (95% CI) of CWS fluoride per a (10%) increase in the proportion of county residents that were Hispanic/Latino was 1.16 (1.10, 1.23).

Conclusions: Fluoride is often present in CWSs at concentrations that exceed the EPA MCL and WHO GDWQ, indicating that fluoride may be an understudied contaminant in public water systems. Fluoride concentrations were significantly greater in Hispanic communities even after adjusting for other sociodemographic and geographic characteristics. Public drinking water exposure estimates for fluoride derived in this study may support future epidemiologic work to address environmental health disparities through assessing optimal concentrations of fluoride in public water systems.

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INTRODUCTION

Fluoridation of public water systems in the US is regarded as a major public health achievement, resulting in a significant reduction in dental caries since the initial integration of manually adjusted fluoridation in community drinking water in 1945 (Centers for Disease Control, 2021; Herschel S. Horowitz, 1996; H. S. Horowitz, Heifetz, Law, & Driscoll, 1968). For example, from 1999-2004 the number of permanent teeth affected by dental caries declined from 6.2 to 2.6 among adolescents aged 12 to 19 (U. S. Department of Health Human Services Federal Panel on Community Water, 2015). Dental caries remains one of the most prevalent adverse health outcomes for US adolescents, especially those who are low-income, with one-quarter of children living below the federal poverty level experiencing dental caries (Dye, Li, & Thorton-Evans, 2012).

Despite the clear health benefits associated with drinking water fluoridation, fluoride is included in the US Environmental Protection Agency (USEPA) list of 91 contaminants in US public drinking water systems with a target maximum contaminant level (MCL) due to potential health risks. In setting the fluoride MCL, the EPA considers related adverse health effects especially dental fluorosis, as there is extensive evidence of risks associated with high exposures to fluoride (EPA, 2011). The US EPA sets MCLs for contaminants with known associated adverse health impacts, and sets these values based on public health benefit, technical feasibility, and the cost of reducing contaminant concentrations for water systems (EPA, 2022). The current MCL for fluoride has been gradually reduced over several decades from its original standard of 12,000 ug/L in 1962 to the current standard of 4,000 ug/L (U. S. Department of Health Human Services Federal Panel on Community Water, 2015). The World Health Organization (WHO) also produces global water quality standards that are published in the Guidelines for Drinking-water Quality (GDWQ), including implementation recommendations and risk management through health-based targets (WHO, 2017). The current WHO GDWQ value for fluoride is 1,500 ug/L (WHO, 2017). In the WHO supporting background document, it is even recommended that some areas where natural fluoride intake is likely to be greater than 6,000 ug/L a day, localities should consider reducing the guidelines to below 1,500 ug/L (WHO, 2004).

Several groups, such as the National Toxicology program under the U.S. Department of Health and Human Services, have evaluated associations between chronic exposure to high concentrations of fluoride and reduced intelligence quotient (IQ) scores and other neurological effects, endocrine disruption, increased risk of bone fractures, and skeletal fluorosis (National Academies of Sciences & Medicine, 2021; Tiemann, 2013). Recent systematic reviews and meta-analysis provide supportive evidence to suggest that high fluoride exposures produce adverse effects on children's neurodevelopment and cognitive health (Choi, Sun, Zhang, & Grandjean, 2012; National Academies of Sciences & Medicine, 2021). A finer resolution study utilizing individual level data built upon the understanding of fluoride exposure effects and found that associations with performance IQ (PIQ) significantly differed based on timing of exposure across prenatal, infancy, and childhood periods (Farmus et al., 2021). Additionally, according to the study, these critical windows of adverse exposure effects may potentially differ for boys and girls.

Emerging evidence regarding the association between fluoride and adverse health outcomes raises concerns about potential disparities in high exposures across US subgroups. Previous studies indicate that Hispanic communities, Tribal communities, and communities in the Southwestern region of the US are supplied by CWSs that are more likely to exceed MCLs for other contaminants such as arsenic, nitrate, and uranium (Hoover, Gonzales, Shuey, Barney,

& Lewis, 2017; Anne E. Nigra & Navas-Acien, 2020). Additionally, counties with higher proportions of Hispanic/Latino residents have elevated estimated CWS arsenic and uranium exposures (Martinez-Morata et al. 2022). Although monitoring reports of SDWA regulation violations found that nearly 20% of CWS with infringements violated a contaminant MCL or treatment technique (TT), the severity of these potential health threats remains understudied (A. E. Nigra et al., 2020; Rubin, 2013). Exploring patterns of demographic inequalities in public water contaminant exposures may inform future public health interventions, influence regulatory action to eliminate exposure injustices, identify relevant exposure sources, and ultimately support efforts to reduce related adverse health outcomes.

Despite the known benefits and potential adverse health outcomes related to fluoride across different levels of chronic exposure, there are currently no nationwide estimates of fluoride exposure in public drinking water across the US that can be leveraged for epidemiologic study. Therefore, the objectives of this study were to a) estimate fluoride exposure in CWSs across the US, b) characterize potential sociodemographic or regional inequalities in CWS fluoride, and c) to determine if racial/ethnic composition was associated with CWS fluoride exposure, per a 10% increase in the proportion of residents who are non-Hispanic Black, American Indian/Alaskan Native, Hispanic/Latino, and non-Hispanic White. We evaluated the following subgroups in our analysis: US region, sociodemographic county clusters, population-served size, source water type, and CWSs which serve correctional facilities. Previous studies identified significantly higher arsenic, nitrate, and uranium exposures for CWSs serving Hispanic and Tribal communities, populations served by smaller CWSs, and in CWSs in the Southwest US region, thus we predicted that CWS fluoride concentrations would be highest among similar communities and that fluoride concentrations would be greater in counties with a higher proportion of Hispanic/Latino residents (I. Martinez-Morata, 2022; A. E. Nigra et al., 2020)

MATERIALS AND METHODS

The US EPA collects compliance monitoring records for regulated drinking water contaminants in public water systems every six years, as required by SDWA (EPA, 2016a). These data are collected through the Information Collection Request process, and voluntarily submitted by states, territories, and tribal authorities. The compliance monitoring data used in this study was collected from the Third Six-Year Review (SYR3) and covers years 2006-2011. The database includes roughly 13 million analytic records from 95% of total public drinking water systems, which serve a total of 290 million people annually (92% of the total population served by public water systems nationwide). The EPA sets standards for routine compliance monitoring water sampling and testing methods and sets compliances testing schedules (EPA, 2016b). The EPA also conducts extensive quality assurance and control evaluations of the SYR3 data before it is published. Some states and tribal regions (Colorado, Delaware, Georgia, Mississippi, EPA regions 2, 6, 7, and 10) did not submit water contaminant reports to the SYR3 (EPA, 2016a).

Statistical analysis: CWS-level fluoride exposure estimates. All data management and analyses were managed in R statistical software (version 4.1.1). To develop 2006-2011 fluoride estimates at the CWS level, we followed a previously published data analysis protocol (A. E. Nigra et al., 2020). Briefly, we evaluated a total of N = 221,183 fluoride monitoring records from 2006-2011. Although each fluoride record may have a different corresponding analytical limit of detection (LOD), the EPA set the maximum allowable LOD for fluoride at 10 ug/L for this time period. Fluoride concentrations that were reported below the LOD were replaced with value of the LOD divided by the square root of two. We used the record-specific LOD when available, and the value of the EPA's maximum LOD for records which a) did not report a record-specific LOD, b) did not report the LOD units in either µg/L or mg/L, c) reported only the minimum reporting level, d) reported the LOD as 0, or e) reported the LOD as greater than 5 µg/L, as these were considered unreliable.

A total of 178,704 (69.7%) records reported values above the LOD. For each CWS, we averaged fluoride concentrations to the overall 2006-2011 time period. We accounted for reported treatment within each calendar year before averaging concentrations to the six-year time period. Within a calendar year, when the average concentration of fluoride in "raw" samples was higher than the average in "finished" samples, we calculated the yearly average using "finished" samples only to reflect fluoride concentrations that would be distributed to customers. Six-year average fluoride concentrations were then merged with other descriptive information for each CWS from the Safe Drinking Water Information System (SDWIS) database, including the counties-served by each CWS, the number of people served, if the system is tribal or not, and the type of source water. CWSs that reported serving zero people were excluded from the analysis. There were no missing CWSs that could not be merged to the SDWIS database, though some CWSs serve multiple counties and have multiple records.

Statistical analysis: Distributions nationwide and stratified by subgroups. We compared the 75th percentile, 95th percentile, and arithmetic mean of fluoride concentrations, and the percent of systems exceeding the EPA MCL and WHO GDWQ for all CWSs nationwide, and across the following subgroups previously described and defined in detail: source water type, size of population served, US region, sociodemographic county-cluster, and CWSs serving correctional facilities (total N=32,495) (A. E. Nigra et al., 2020). Source water type was assigned for each CWS as reported in SDWIS by either groundwater or surface water. The size of the population served by CWSs was defined from standard EPA categories (≤500 persons, 501-3,300 persons, 3,301-10,000 persons, >10,000 persons). Regions were created for Pacific Northwest (ID, MT, OR, WA, WY), Southwest (AZ, CA, CO, NM, NV, TX, UT), Central Midwest (KS, MO, ND, NE, SD), Eastern Midwest (IA, IL, IN, MI, MN, OH, WI), Southeast (AL, AR, FL, GA, KY, LA, MS, TN, OK), Midatlantic (CT, DE, DC, MD, NJ, NY, PA, RI), New England (MA, ME, NH, VT), and Alaska (AK) and Hawaii (HI) based on Ayotte et. al. 2017 (Environ Sci Technology) and US Census Bureau Regions and Divisions (US Census (Bureau, 2019).

Sociodemographic county-clusters were previously developed by a different research group to enable the comparison of county-level outcomes while accounting for sociodemographic makeup of county population (Wallace, Sharfstein, Kaminsky, & Lessler, 2019), and were categorized as: Semi-Urban, High Socioeconomic Status (SES); Semi-Urban, Mid/Low SES; Semi-Urban, Hispanic; Mostly Rural, Mid-SES; Rural, Mid/Low SES; Young, Urban, Mid/High SES; Rural, American Indian; and Rural, High SES. CWSs that exclusively served correctional facilities were identified by a water system name keyword search for “prison”, “correction”, “corr”, “juvenile”, “detention”, “jail”, “penitentiary”, “women”, “tdcj”, “adoc”, “adc”, and “sheriff” (total N=3,294). We assessed statistical significance for differences in fluoride concentrations across subgroups via non-parametric Kruskal-Wallis tests.

County-level maps: Population-weighted, CWS-level fluoride exposures. We also aggregated CWS fluoride estimates to the county-level, as previously described in detail (A. E. Nigra et al., 2020). County-level fluoride averages weight the contribution of each CWS to the total county average by the number of people served by that CWS. To identify spatial patterns in fluoride exposure estimates throughout the US, we generated county-level maps of CWS fluoride exposures nationwide using the “maps” R package (Becker, 2018). We were unable to aggregate CWS-level data to a finer geographic resolution (e.g., zip code) because only county-served was consistently and reliably reported in SDWIS. Counties with missing or inadequate CWS-level data were treated as missing, as previously described in detail.

Statistical analysis: Spatial lag regression. To determine if county-level racial/ethnic composition was associated with CWS fluoride exposure levels, we downloaded several county-level sociodemographic variables. County-level racial/ethnic composition variables were derived from 2011 US Census Population Estimates and included the proportion of residents who are American Indian or Alaskan Native (hereafter referred to as American Indian/Alaskan Native), Asian, Native Hawaiian or Other Pacific Islander, Hispanic or Latino (hereafter referred to as Hispanic/Latino), non-Hispanic Black or African American (hereafter referred to as non-Hispanic Black), and non-Hispanic White (US Census Bureau, 2011). County total population and population density (population per square mile) were also retrieved from the US Census. The percent of adults with a high school diploma was derived from the 2007-2011 US Census American Community Survey, and median household income was derived from the 2011 Small Area Income and Poverty Estimates and 2010-2011 National Center for Education Statistics data (County Health Rankings & Roadmaps, 2019). We estimated the percent of public drinking water supplied by groundwater sources (versus surface water sources) from estimates of total groundwater and surface water withdrawn for public drinking water calculated by the US Geological Survey for 2010, as previously described (Maupin et al., 2014; A. E. Nigra et al., 2020).

We assessed spatial autocorrelation (dependence) in CWS fluoride exposure at the county-level using Moran's I (a correlation coefficient assessing global spatial autocorrelation). We defined neighbors using a simple queen's contiguity matrix (i=1 for neighbors, i=0 for non-neighbors). Moran's I indicated significant global spatial autocorrelation (I= 0.4777460828, $p<2.2e-16$), suggesting that effect estimates from ordinary least squares (OLS) models may be biased. To identify whether a spatial error or spatial lag model would be the most appropriate fit for our analysis, we conducted a Lagrange Multiplier diagnostic for spatial dependence for models assessing the 10% higher proportions of residents in each of the subgroups including Hispanic/Latino, non-Hispanic Black, American Indian, and non-Hispanic White via the Lagrange Multiplier function lagsarlm in the "spatialreg" R package (RDocumentation, 2021).

P-values for both spatial lag and spatial error parameters were <0.001, and we proceeded using spatial lag models because effect estimates were larger for the majority of models we assessed (R.J.G.M Florax et al, 2005). We evaluated the geometric mean ratio (GMR), 95% CIs, and corresponding percent differences of county-level CWS fluoride exposure per 10% higher proportion of residents who were Hispanic/Latino, non-Hispanic Black, American Indian, and non-Hispanic White. For monitoring water quality standards, geometric means are often utilized over other calculations, such as arithmetic mean, as the averaging of logarithmic values for contaminant concentrations is able to dampen the effect of very high or very low values. Model 1 adjusted for the percent of public drinking water served by a groundwater source, population density, percent of adults with a high school diploma, and median household income. To determine if associations with racial/ethnic composition were explained by CWS fluoridation, Model 2 further adjusted for the county-level proportion of public drinking water from CWSs which report fluoridation via SDWIS, weighted by the population served by each CWS.

RESULTS

Nationwide detections and MCL exceedances. Out of 256,237 total routine compliance monitoring records available in the SYR3, fluoride concentrations were detected above the LOD for 178,704 (69.7%) records (Table 1). We developed 2006-2011 fluoride exposure estimates for 32,495 CWSs. Of these, 4.5% (N=1,456) had fluoride concentration estimates above the World Health Organization Guideline for drinking water quality (WHO GDWQ, X μg/L) and 0.3% (N=99) had fluoride concentration estimates above the US EPA MCL (4,000 μg/L). Nationwide, the 50th, 90th, and 95th percentiles of estimated CWS fluoride CWSs from 2006-2011 were 183, 1,000, and 1,428 μg/L (Table 1).

Fluoride exposures stratified by source water type, CWS size, and correctional facilities. Fluoride exposures varied across source water types, as CWSs which relied on groundwater had higher mean, 75th, and 95th percentile concentrations (388, 1,040 and 1,485 μg/L) than CWSs which relied on surface water (240, 651, and 914 μg/L) (Table 2). Fluoride concentrations also differed significantly across categories of population served size ($p<0.001$). The 75th and 95th percentile fluoride concentrations were larger for smaller CWSs serving ≤500 people (939, 1,460 μg/L) and medium sized CWSs serving 500-3,300 people (1,177, 1,475 μg/L) and 3,301-10,000 people (1,115, 1,380 μg/L, respectively) than CWSs serving the largest populations with >100,000 people (681, 851 μg/L). Throughout the US, 75th, 95th fluoride percentile concentrations (μg/L) for CWSs serving correctional facilities were similar to those for all CWSs (753, 1,111 μg/L versus 1,000, 1,428 μg/L).

Fluoride exposures stratified by US regions and sociodemographic clusters. CWS fluoride concentrations differed significantly difference by US regions ($p<0.001$, Table 2). Mean (95% CIs) CWS fluoride concentrations were highest among CWSs in the Southwest (517 μg/L, 95% CI 512, 542), Eastern Midwest (524 μg/L, 95% CI 509, 540) and Central Midwest (415 μg/L, 95% CI 394, 435). Similarly, 75^{th}, 95^{th} percentile fluoride concentrations were highest in the Southwest, Eastern Midwest, and Central Midwest.

CWS fluoride concentrations were also significantly different across sociodemographic clusters ($p<0.001$). Mean (95% CI) fluoride concentrations (μg/L) were highest among CWSs classified as serving Semi-Urban, Hispanic counties (605 μg/L, 95% CI 582, 628), followed by CWSs classified as serving Rural, High SES counties (457 μg/L, 95% CI 438, 476), and CWSs classified as serving Rural, American Indian counties (432 μg/L, 95% CI 381,484) (Table 2). We observed similar rankings when comparing 75^{th} and 95^{th} percentile concentrations.

Spatial lag regression. Geometric mean ratios and 95% confidence intervals for county-level CWS fluoride concentrations, per 10% increase in the proportion of residents fluctuated across racial/ethnic groups. In Model 1 which adjusted for population density, the percent of public water sourced from groundwater supplies, median household income, and the percent of adults with a high school diploma, the GMR (95% CI) was largest for Hispanic/Latino residents (1.15, 95% CI 1.09, 1.21). Following racial/ethnic groups were BIPOC residents (1.09, 95% CI 1.05, 1.14), non-Hispanic White residents (1.09, 95% CI 1.04, 1.14), American Indian/ Alaskan Native residents (1.05, 95% CI 0.95, 1.16), and non-Hispanic Black residents (1.00, 95% CI 0.93, 1.09). Model 2, which further adjusted for the percent of public water that was fluoridated, produced similar results with slight increases in GMR (95% CI) for American Indian/Alaskan Native residents (1.11, 95% CI 1.00, 1.23), non-Hispanic Black residents (1.05, 95% CI 0.96, 1.13), and for Hispanic/Latino residents (1.16, 95% CI 1.10, 1.23).

DISCUSSION

Community water system (CWS) fluoridation is widespread; the Centers for Disease Control (CDC) estimates that in 2012, 200 million people in the US were served by 12,341 community water systems that manually added fluoride (U. S. Department of Health Human Services Federal Panel on Community Water, 2015). Over 80% of US residents rely of public drinking water systems, and public drinking water is the major source of fluoride exposure, accounting for 40-70% of exposure in children and 60% in adults (U. S. Department of Health Human Services Federal Panel on Community Water, 2015). Data indicates that fluoride exposure levels have increased in the last 40 to 50 years, which has also heightened adverse effects on teeth of adults and children in the form of dental fluorosis (EPA, 2011). A recent analysis of NHANES data found that in the ten year period from 2001 to 2011, national rates of dental fluorosis increased from 29.7% to 61.3% (Wiener, Shen, Findley, Tan, & Sambamoorthi, 2018). Other health risks from chronic exposure to high levels of fluoride in public drinking water are less well studied and characterized.

Although CWSs in the US began manually fluoridating public water supplies as early as 1945, our study provides the first nationwide exposure estimates of CWS fluoride nationwide and across subgroups (Centers for Disease Control, 2021). Our findings indicate that during the time period of 2006-2011, 4.5% of CWSs reported mean fluoride concentrations above the WHO GDQW, and that significant variability in CWS fluoride exposure exists across geographic and sociodemographic groups. Despite several historical reductions in the EPA's MCL for fluoride and emerging epidemiologic evidence supporting an association between fluoride exposure and child adverse neurocognitive outcomes, epidemiologic studies assessing the association specifically between water fluoride exposure and related health outcomes remain relatively sparse (National Academies of Sciences & Medicine, 2021; Tiemann, 2013).

Our finding that a higher proportion of Hispanic/Latino residents was associated with elevated CWS fluoride exposure estimates at the county-level raises significant environmental justice concerns. These findings are consistent with previous analyses of national water utility data indicating that SDWA health violations are most common in communities with higher populations of Hispanic residents, and prior work finding higher CWS uranium, arsenic, and nitrate concentrations for public water systems serving Hispanic/Latino communities (Switzer & Teodoro, 2017). The exact mechanisms influencing the disparities in CWS fluoride exposure among Semi-Urban, Hispanic communities cannot be fully explained in our study. However, structural racism underlies inequalities in other CWS exposures through ineffective regulatory procedures, inequalities in land use patterns, differences in anthropogenic uses, geologic processes, technical and financial support for CWS, and other policies embedded within society (Bailey et al., 2017; Balazs & Ray, 2014). Reports on environmental health risks have additionally cited past inadequacies in using Hispanic identifiers, limited sample size in data collection, and unequal enforcement of health safety laws which further exacerbate various environmental justice issues faced by Hispanic communities (Metzger, Delgado, & Herrell, 1995). In light of these recent findings of elevated exposure to arsenic, uranium, nitrate, and now fluoride in Hispanic/Latino communities, improving infrastructure, technical and financial support, regulatory monitoring, and upscaled public health research is necessary to determine the full scale of socioeconomic and health impacts on these communities and for infrastructure investment prioritization.

Fluoride is easily retained in minerals and rocks in the lithosphere and is widely dispersed in the earth's crust, comprising in up to 0.06-0.09% of the earth's crust (Chuah et al., 2016). Fluoride can occur in groundwater at significantly high concentrations in environments with a geologic abundance of subterranean minerals and rocks (García & Borgnino, 2015). Similar to previous findings for uranium and arsenic, CWSs dependent on groundwater sources had greater fluoride exposure estimates. Fluoride is challenging to remove from water sources, with reverse osmosis filtration and activated alumina defluorination as the two most common concentration reduction methods (Indermitte, Saava, & Karro, 2014).

Our analysis has several limitations worth highlighting. Evaluation of nationwide CWS fluoride exposures was limited to the routine compliant monitoring records in the SYR3 obtained from EPA. Missing compliance monitoring records from states and tribal regions that did not submit compliance monitoring records to the SYR3 (Colorado, Delaware, Georgia, Mississippi, EPA regions 2, 6, 7, and 10) may have contributed to potential bias, especially in our analyses stratified by US region. To minimize information bias, CWS fluoride estimates of six-year averages were used to account for the six-year compliance monitoring period that the EPA requires for inorganic contaminants (water systems were required to test at least once every three years, depending on source water type). Due to limited available data, as nationwide CWS distribution boundaries are not publicly accessible, we were unable to aggregate for exposure estimates at other geographic units such as self-defined neighborhood, census tract, zip code, etc. which may have better reflected consumer exposure. Without such option to evaluate finer resolution profiles of CWS service areas, geographic aggregations reliant on county-level data are limited in assessing sociodemographic disparities (VanDerslice, 2011). Our paper is solely focused on a nationwide assessment of fluoride exposures in regulated CWS throughout the US, thus the scope of our study was unable to capture assess elevated exposures in subgroups that relied on private water systems not subject to EPA regulation.

Additional exploration is needed to clarify the extent at which chronic exposure to high levels of fluoride in public drinking water impacts health outcomes. Investigations can improve upon previous studies and our understanding of the association between fluoride exposure with carcinogenicity, IQ and other neurological effects, endocrine disruption, risk of bone fractures, and skeletal fluorosis. As our study was preliminary in establishing nationwide estimates of fluoride exposure in CWSs and identifying highly exposed subgroups, research is still needed to identify mechanisms underlying fluoride exposure disparities (e.g., fluoridation policies, groundwater fluoride concentrations, etc.).

Prospective work should specifically investigate disparities within Hispanic/Latino and American Indian communities, residents whose CWS relies on groundwater, and those in the Southwest, Central Midwest, and Eastern Midwest. Obtaining data to produce finer resolution geographic analyses of racial and ethnic inequalities in CWS exposures across regions with the highest CWS fluoride exposure estimates (e.g., census tract level analyses in the Southwest for states with publicly available CWS distribution boundaries available), can generate more appropriate community exposure estimates and allow for greater control of potential confounding factors. It may be beneficial to examine if temporal trends in CWS fluoride concentrations indicate that exposure disparities are consistent or are changing over time and attempt to contextual the mechanisms which allow these elevated fluoride concentrations to occur in CWS subgroups.

As findings in our study demonstrate that elevated fluoride exposures are experienced the most in Hispanic/Latino populations, the EPA and other federal agencies must prioritize addressing this environmental justice concern and characterizing the severity of these impacts on health disparities. The current results also support additional work to identify further inequalities in public drinking water exposures for other EPA regulated contaminants. Specific attention is needed to correct federal oversight in order to improve drinking water quality for all communities and meet environmental justice standards.

TABLES

Table 1. **Distribution of estimated fluoride in community water systems (CWSs) across the US in µg/L, 2006-2011 (N= 32,495 CWSs).** Estimates are based on N= 256,237 routine compliance monitoring records reported in the US EPA's database supporting the Third Six Year Review of Contaminant Occurrence (N= 178,704 of these records had fluoride concentrations measured above the limit of detection). The EPA method detection limit for fluoride during the Third Six Year Review period (2006-2011) was 0.01 µg/L.

N CWSs	32,495
Arithmetic mean	376
50%	183
90%	1000
95%	1428
N (%) above WHO GDWQ (1,500 µg/L)	1,456 (4.5%)
N (%) above EPA MCL (4,000 µg/L)	99 (0.3%)

WHO = World Health Organization. GDWQ = Guideline for drinking water quality.
EPA = Environmental Protection Agency. MCL = maximum contaminant level.

Table 2. **Mean, 75th percentile, and 95th percentile of fluoride concentrations (µg/L) in community water systems (CWSs) nationwide and stratified by subgroup from 2006-2011 (N=32,495 CWSs).**

	N	N (%)> MCL	N (%)> WHO GDWQ	Arithmetic mean (95% CI)	75% (95%)
All CWSs	32,495	99 (0.3%)	1,456 (4.5%)	376 (370,383)	1,000 (1428)
Source water type					
Groundwater [a]	29,928	99 (0.3%)	1,443 (4.8%)	388 (381,395)	1,040 (1485)
Surface water	2,567	0 (0%)	13 (0.5%)	240 (227,253)	651 (914)
P-value					<0.001
Size of population served [b]					
≤500	19,436	81 (0.4%)	920 (4.7%)	354 (345,362)	939 (1,460)
500-3,300	7,827	17 (0.2%)	368 (4.7%)	410 (396,423)	1,177 (1,475)
3,301-10,000	2,806	1 (0%)	110 (3.9%)	411 (392,429)	1,115 (1,380)
10,001-100,000	2,136	0 (0%)	55 (2.6%)	411 (392,431)	971 (1,260)
>100,000	290	0 (0%)	3 (1%)	387 (342,431)	681 (851)
P-value					<0.001
Region					
Alaska/Hawaii	418	0 (0%)	1 (0.2%)	85 (66,103)	250 (409)
Central Midwest	2,436	5 (0.2%)	94 (3.9%)	415 (394,435)	1,044 (1,406)
Eastern Midwest	4,887	3 (0.1%)	260 (5.3%)	524 (509,540)	1,295 (1,530)
Mid-Atlantic	3,641	1 (0%)	15 (0.4%)	114 (103,125)	329 (535)
New England	1,634	0 (0%)	77 (4.7%)	323 (295,350)	1,025 (1,479)
Pacific Northwest	3,848	4 (0.1%)	100 (2.6%)	254 (240,269)	650 (1,000)
Southeast	7,107	27 (0.4%)	271 (3.8%)	310 (297,323)	720 (1,271)
Southwest	8,524	59 (0.7%)	638 (7.5%)	527 (512,542)	1,277 (1,880)
P-value					<0.001
Sociodemographic county cluster[c]					
Semi-Urban, High SES	12,531	8 (0.1%)	349 (2.8%)	306 (298,315)	836 (1,233)
Semi-Urban, Mid/Low SES	1,325	8 (0.6%)	69 (5.2%)	376 (343,410)	969 (1,524)
Semi-Urban, Hispanic	4,536	50 (1.1%)	391 (8.6%)	605 (582,628)	1,376 (2,020)

Mostly Rural, Mid-SES	7,837	9 (0.1%)	327 (4.2%)	322 (310,334)	930 (1400)
Rural, Mid/Low SES	499	0 (0%)	24 (4.8%)	377 (337,418)	1,019 (1403)
Young, Urban, Mid/High SES	1,022	2 (0.2%)	12 (1.2%)	254 (231,277)	550 (829)
Rural, American Indian	437	1 (0.2%)	18 (4.1%)	432 (381,484)	1,042 (1348)
Rural, High SES	4,448	21 (0.5%)	269 (6%)	457 (438,476)	1,270 (1649)
P-value					<0.001
Correctional facility CWSs	192	0 (0%)	5 (2.6%)	294 (234,354)	753 (1,111)
P-value					0.058

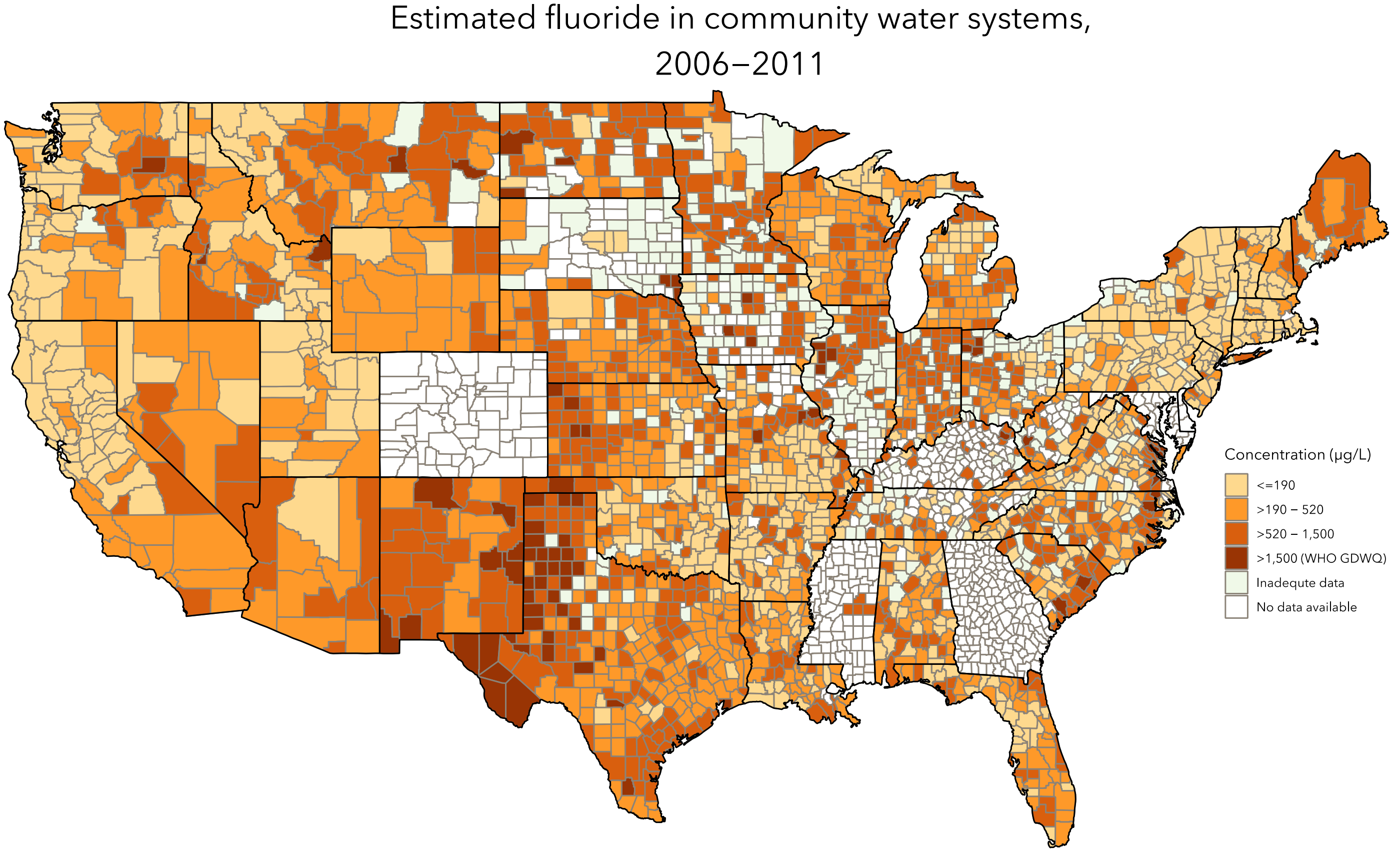
P-values are from non-parametric Kruskal-Wallis test. WHO = World Health Organization. GDWQ = Guideline for drinking water quality. EPA = Environmental Protection Agency. MCL = maximum contaminant level. [a]CWSs served by groundwater include those served by surface water under the influence of groundwater and groundwater under the influence of surface water. [b]Categories of population served are standard U.S. EPA categories. Population served is adjusted total population served, which accounts for systems that sell or purchase water and avoids overcounting. [c]Very few CWSs served more than one county; of these, approximately half served counties categorized to different sociodemographic county-clusters (e.g., NY7003493 serves New York, New York (Young, Urban, Mid/High SES) and Bronx, New York (Semi-Urban, Hispanic). Sociodemographic clusters were classified based on Wallace et al. (2019) (Wallace et al.). These CWSs are represented for each county that they serve in the sociodemographic county-cluster analyses (N = 32,653). States included in geologic regions are: Alaska/Hawaii (AK, HI), Central Midwest (ND, SD, NE, KS, MO), Eastern Midwest (WI, IL, IN, MI, OH, MN, IA), Mid-Atlantic (PA, MD, DC, DE, NY, NJ, CT, RI), New England (MA, VT, NH, ME), Pacific Northwest (WA, OR, MT, WY, and ID), Southeast (OK, AR, LA, MS, AL, FL, GA, TN, KY, SC, NC, VA, WV), and Southwest (CA, NV, UT, CO, AZ, NM, TX).

Table 3. Geometric mean ratios (GMR) and 95% CI of county-level community water system (CWS) fluoride concentrations across the US, per a 10% increase in the proportion of residents who are non-Hispanic Black, American Indian/Alaskan Native, Hispanic/Latino, and non-Hispanic White. Spatial autocorrelation was modeled in Lagrange models with autoregressive correlation structure. Model 1 adjusts for population density, the percent of public water sourced from groundwater supplies, median household income, and the percent of adults with a high school diploma. Model 2 further adjusts for the percent of public water that was fluoridated.

CWS Served	N	GMR (95% CI)
% non-Hispanic Black	1,555	
Model 1		1.00 (0.93, 1.09)
Model 2		1.05 (0.96, 1.13)
% American Indian/Alaskan Native	1,423	
Model 1		1.05 (0.95, 1.16)
Model 2		1.11 (1.00, 1.23)
% Hispanic/Latino	1,961	
Model 1		1.15 (1.09, 1.21)
Model 2		1.16 (1.10, 1.23)
% non-Hispanic White	2,111	
Model 1		1.09 (1.04, 1.14)
Model 2		1.09 (1.04, 1.14)
% BIPOC	2,078	
Model 1		1.09 (1.05, 1.14)
Model 2		1.09 (1.05, 1.14)

FIGURES AND FIGURE LEGENDS

Figure 1. County-level weighted average of fluoride concentrations in community water systems (CWSs) from 2006-2011 (N= 32,495 CWSs serving N= 2,152 counties). Average concentrations were weighted by the population served by each CWS to estimate the county-level weighted average CWS concentrations. Counties which were not represented by any CWSs in the SYR3 database are labeled as "No data available." Counties with "Inadequate data" did not have CWS data representing at least 50% of the public water reliant population. The highest concentration category (>1,500 µg/L) represents counties with a weighted average fluoride concentration exceeding the World Health Organization's (WHO) guideline for drinking water quality (two of these counties had weighted averages exceeding the EPA's maximum contaminant level of 4,000 gµ/L). The two lowest concentration categories correspond to quantiles splitting the other counties into two equal groups.



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