Mapping the Distribution of Per- and Polyfluoroalkyl Substances (PFAS) in California's Water Systems: Implications for Monitoring and Health Protection

Teresa C. Echevarria

ABSTRACT

Understanding the potential biological impacts of Per- and Polyfluoroalkyl Substances (PFAS) on human health underscores the importance of robust water quality monitoring protocols, particularly in California. The current monitoring protocol for PFAS, such as Perfluorooctanoic Acid (PFOA), centers around areas with historical PFAS use, such as airports and landfills. In addition, existing spatial analysis models rely on outdated and limited datasets, potentially skewing perceptions of contamination. This study uses updated data from the Fifth Unregulated Contaminant Monitoring Rule from 2023-2025, which includes new data on 29 different PFAS, to map the spatial distribution of PFOA in Public Water Systems (PWSs). These water systems are then visualized with Public Supply Wells, Investigative Sites, and Regional Waterboards to understand how these factors impact or are impacted by PFOA contamination and how regulatory agencies can pursue monitoring efforts. The findings of this study illuminate the interplay of factors contributing to PFOA contamination in California. Out of 2324 samples, 107 exceeded the Maximum Contaminant Level (MCL) for PFOA, as proposed by the Environmental Protection Agency (EPA), distributed across 44 distinct PWSs. Samples above the MCL were concentrated in urban settings, with a high presence of industrial facilities, corresponding to previous studies on the occurrence of PFOA in water systems. However, sampling was generally situated in these urban settings, underscoring the need for concentrated monitoring efforts in Northern and Eastern California rural communities, specifically within the Lahontan and North Coast Regional Water Board Boundaries.

KEYWORDS

Perfluorooctanoic Acid, public health, groundwater, spatial analysis, public water systems, risk

INTRODUCTION

The industrialization of the 20th century spurred the emergence of numerous polluting industries, which continue to exert a significant impact on global health (Rahman et al. 2021). Analyzing the effects of industrial byproducts on communities and their surrounding areas is imperative to mitigate health risks associated with pollution from these industries. Assessing water quality, among other potential routes of exposure, enables communities to comprehend how environmental contaminants may affect regional ecosystems and human health. This understanding is crucial for identifying and addressing disparities in environmental pollution burdens among different demographic groups and implementing preventive measures against future harm (Schaider et al. 2019). One such group of manmade chemicals that warrants attention is Per and Polyfluoroalkyl Substances (PFAS), extensively used in industrial manufacturing and consumer products. The discovery of elevated concentrations of PFAS in drinking water sources is becoming increasingly prevalent in communities across the United States (Fenton et al. 2021). These contaminants pose complex challenges for regulators striving to balance industrial interests and environmental and public health concerns (Brennan et al. 2021).

Per- and polyfluoroalkyl substances (PFAS) are categorized as persistent organic pollutants and emerging contaminants due to their distinctive properties, including hydrophobicity, lipophobicity, and high stability, which have led to their widespread utilization in consumer products, industrial facilities, landfills, and wastewater treatment plants (Crone et al., 2019). Their exceptional stability and durability have made them particularly appealing for military and firefighting personnel, as they are resistant to heat, water, oil, and degradation over time, primarily employed in firefighting foams and various industrial applications (Brennan et al. 2021). These attributes contribute to their potential for bioaccumulation, facilitating their pervasive distribution and raising concerns about potential human health hazards (Kurwadkar et al. 2022).

Health experts have identified several risks associated with PFAS exposure, including alterations in immune and thyroid function, liver disease, dysregulation of lipids and insulin, kidney dysfunction, reproductive health issues, and some cancers (Fenton et al. 2021). Among the numerous PFAS compounds, perfluorooctanoic acid (PFOA) is among the most extensively researched regarding its health effects and monitoring. Nevertheless, understanding PFAS-related health impacts remains limited compared to other chemical substances, underscoring the necessity for ongoing scrutiny and refinement of current monitoring protocols (Domingo and Nadal 2019).

Emerging insights into the toxicity and persistence of PFAS in aquatic environments have prompted extensive research into the risks posed by persistent chemical pollutants. In California, although PFOA has largely been phased out of industrial use, monitoring efforts are typically focused on proximity to investigation sites and constrained by the limitations of existing technology (Veasy et al. 2022). This raises concerns about how current monitoring practices might obscure contamination across the state and hinder a comprehensive understanding of the spatial distribution of PFOA occurrence in California. By examining potential risk factors, such as sites where PFOA-containing agents were historically used (e.g., Department of Defense facilities, airports, landfills), it may be possible to gain insights into areas where elevated concentrations of PFOA are likely to be found.

This study aims to assess PFOA monitoring practices in California and identify gaps in sampling coverage across the state. The hypothesis posits that sampling efforts are primarily concentrated in highly urbanized areas, potentially overlooking rural communities. Furthermore, it is speculated that sampling strategies may fail to capture potential risk factors present in rural regions. To understand these questions, I ask which samples were above the recommended contamination levels allowed in water systems, where these samples are located throughout the state, and how these samples compare to Regional Water Board Boundaries and risk factors. To elucidate this phenomenon, the study will initially map all known contaminated well sites in California, alongside identified risk factors and the boundaries of regional water boards, to discern how sampling efforts are distributed in relation to perceived risks and across regulatory jurisdictions.

BACKGROUND

PFAS Monitoring Framework

As early as 1998, the Environmental Protection Agency (EPA) of the United States began investigating the health and environmental impacts of PFAS, following precautionary studies that showed that these chemicals may be influencing health effects. In 2009, the EPA published provisional health advisories for PFOA and PFOS, following this with publishing the Third Unregulated Contaminant Monitoring Rule (UCMR 3), which required states to monitor six different PFAS under the Safe Drinking Water Act. The Safe Drinking Water Act amendments require that every 5 years, the EPA issue a new list of no more than 30 unregulated contaminants to be monitored by public water systems (PWSs). UCMR 3 required the monitoring of 30 contaminants, including perfluorooctanesulfonic acid (PFOS), perfluorooctanoic acid (PFOA), perfluorononanoic acid (PFNA), perfluorohexanesulfonic acid (PFHxS), perfluoroheptanoic acid (PFHpA), and perfluorobutanesulfonic acid (PFBS), from 2012-2015 (Apex AP 2022). In 2021, the EPA expanded the number of PFAS being monitored when publishing the protocol for UCMR 5 to test for 29 different PFAS. This data is now being published as of January 2024 (U.S. Environmental Protection Agency 2021). Between these two datasets, the EPA also published interim health advisories for PFOA and PFOS, indicating that some negative health effects may occur with concentrations of PFOA or PFOS in water that are near zero. The EPA followed this by announcing $1 billion in newly available funding to help states implement PFAS testing and treatment at PWS and address PFAS contamination. This is particularly to address PWS in small or disadvantaged communities nationwide (U.S. Environmental Protection Agency 2022).

PFAS Monitoring California

California has emerged as a leader in water quality monitoring, surpassing many states with similar funding and resources. This leadership is evidenced by initiatives such as the Groundwater Ambient Monitoring and Assessment (GAMA) Program and the Surface Water Ambient Monitoring Program (SWAMP). A significant milestone was reached in 2012 with the passage of Assembly Bill 685, which enshrined the Human Right to Water law. This legislation recognizes the universal entitlement to clean, safe, and affordable drinking water for all residents, extending its provisions to communities served by various water systems, including community water systems (CWS), state small water systems, domestic wells, and small systems. Despite these efforts, approximately 10% of California's public drinking water fails to meet state quality standards, affecting an estimated 6 million residents served by systems that have violated these standards since 2012 (Pace et al. 2022). Monitoring challenges are particularly pronounced for domestic wells compared to CWS, as the latter are subject to regulatory oversight under the Safe Drinking Water Act, whereas domestic wells remain largely unregulated.

In response to emerging concerns about pollutants such as PFAS, California passed Assembly Bill 756 in 2019, empowering the state board to mandate PFAS monitoring by public water systems. This bill also requires water systems to take action if PFAS levels exceed prescribed limits. Similarly, in September 2020, California expanded regulations to include firefighting foams, a significant source of PFAS contamination (Brennan et al. 2021). While these measures prohibit manufacturing and selling PFAS-containing foams, they do not address previously contaminated areas.

The U.S. EPA sampled 2,807 public supply wells in California from 2012-2015, compiling data into UCMR 3. However, during this time, testing mainly occurred near high-risk sites such as airports with fire training areas, landfills, and Department of Defense sites. This was expanded in 2020, with orders sent to 224 public water systems with 887 wells to investigate further PFAS contamination (State Water Resources Control Board 2024). Nonetheless, these testing locations still do not cover all of California, leaving many rural and urban areas without PFAS monitoring data. Combined with the fact that most monitoring data points only record minimum contaminant levels, this leaves a large portion of the state without accurate monitoring data.

Human Health Implications of PFAS

Managing classes of chemicals through risk assessment can serve as a crucial tool in mitigating adverse effects on human and ecological health. For PFAS, effective regulation of their use and distribution is of paramount importance due to the persistent and potentially harmful nature of this chemical group. The versatile chemical structure of PFAS enables multiple functions within common industrial products such as surfactants, friction reducers, and water, dirt, and oil repellents (Kwiatkowski et al. 2020). Factors such as functional groups, carbon chain length, hydrophobicity, and lipophobicity influence the environmental and biological burden of PFAS. Their numerous carbon-fluorine bonds confer thermal stability and resistance to degradation, leading to their classification as "forever chemicals" that accumulate and persist in various environmental compartments, including water, air, sediment, soil, and plants.

Among PFAS compounds, Perfluorooctanoic acid (PFOA) is of particular concern due to its association with health risks such as testicular and kidney cancer. Exposure to PFOA can occur throughout its life cycle, including manufacturing, distribution, use, disposal, or recycling of products containing it (Wee and Aris 2023). As a "long-chain" PFAS, characterized by seven or more fluorinated carbons, PFOA exhibits high toxicity and bioaccumulative potential (Kwiatkowski et al., 2020). The phase-out of these long-chain compounds in favor of shorter-chain alternatives was expected to reduce toxicity. However, it was later discovered that the shorter-chain variants were even more mobile. The sheer diversity of PFAS chemicals and structures poses challenges for federal and state governments in regulating each type, compounded by limited data on their toxicological effects and persistence (Fenton et al., 2021).

Despite these challenges, some adverse effects associated with PFAS exposure include elevated cholesterol, liver disease, decreased fertility, thyroid disorders, disruptions in hormone functioning, compromised immune response, and developmental abnormalities. Addressing the complex risks posed by PFAS requires a multifaceted approach encompassing robust regulatory frameworks, comprehensive risk assessment, and continued research to elucidate their impacts on human health and the environment.

METHODOLOGY

Information About Current Locations of PFAS

From an intensive agricultural sector and large urban industrial areas, California uses more groundwater than any other state. Elevated concentrations of trace elements along with a wide range of contaminant sources, present risks in the potential to contaminate this groundwater and limit its uses (Belitz et al. 2003). Currently, multiple sectors of the government, along with private organizations, monitor water systems in the state. The Groundwater Ambient Monitoring and Assessment Program, the California government's comprehensive groundwater quality monitoring program, has released multiple maps visualizing PFAS-contaminated wells in California for accessibility to the public and research purposes. The GAMA Groundwater Information System (GAMA GIS) was developed as part of this expansion, as this map integrates, standardizes, and geographically displays groundwater quality information in an accessible platform (California

State Water Resources Control Board 2023). The PFAS Mapping Tool is a subset of this map that integrates information about locations with investigation orders, such as airports, industries, landfills, and military sites. However, it is clear from this tool that there are still large portions of the state left unmonitored, such as areas in Northern California, some regions of Los Angeles, and the Bay Area. These maps were also compiled with the data from UCMR 3, meaning they were slightly outdated during this study.

UCMR 5 Information

To analyze the proportion of public supply wells noted with contamination in 2023, I used data from the EPA's Fifth Unregulated Contaminant Monitoring Rule (UCMR 5). As mentioned, this program extended monitoring notices for 29 different PFAS in 2021, including PFOA. As of January 2024, 24% of the expected results had been published, which is the number of results included in this study. There are two definitions important to understand for this study (U.S. Environmental Protection Agency 2021). First, Maximum Contaminant Levels (MCLs) are the legally enforceable levels of contaminants allowed in water delivered to any public water system user. This is the level at which the EPA will require public water systems to monitor, notify the public, and reduce the level of PFAS in drinking water. Minimum Reporting Levels (MRLs) are the lowest measurable concentration of contamination due to laboratory capacity. On April 10, 2024, the EPA established a new MCL for PFOA as 4 parts per trillion (ppt) or 0.004 ug/L. The current MRL for UCMR 5 is also 0.004 ug/L. Monitoring primarily focuses on reporting PFOS and PFOA concentrations that meet or exceed the EPA's UCMR minimum reporting level (MRL). Monitoring orders for PFAS within this study are still based on the well site's proximity to sites with investigative orders. It is still unknown whether PFAS could be detected in well sites away from sites with investigative notices. Sites with investigative notices are Department of Defense (DoD) Facilities, Airports, Chrome Plating Facilities, Landfills, Publicly Owned Treatment Works (POTW), Refineries and Bulk Terminals.

METHODS

Compiling Data for Spatial Analysis

To conduct a thorough analysis of PFOA in California, it was important to draw data from various sources for different examinations due to the limited capacity of PFOA monitoring nationwide. Data compiled from the Fifth Unregulated Contaminant Monitoring Rule (UCMR5) was employed for further analysis. To reiterate, the MRL is based on laboratory capacity, not health standards, meaning that technology can not properly detect contamination of water samples under 0.004 ug/L. In UCMR 5, these values are denoted as '< MRL'; thus, there are no definitive 0 values for any samples in the dataset. At the time of this study, only 24% of the total results had been published (U.S. Environmental Protection Agency 2021). Despite this, I opted to include this dataset based on my literature review, which suggested that there would be no significant deviation in findings given that sampling is conducted based on proximity to investigative sites. Consequently, shapefiles of all public supply wells in California were utilized for spatial analysis after being obtained through the state water board.

To prepare the data for use in ArcGIS, I found it necessary to summarize the results for the public water system. Since the total dataset was not published, there were water systems that had more samples than others. To standardize this, I utilized Excel tools and took the maximum results at each site. I also did some brief analysis of these water systems to determine if the samples were above the MCL, the number of samples taken, and the size of the public water system. This dataset, which I titled "PFOA Summarized," was joined to a dataset of all California public supply wells (PWS). Using symbology, well sites above the MCL were denoted with red, and those under the MCL were denoted in yellow. However, as mentioned before, since the MCL and MRL for UCMR 5 are now the same, this meant that essentially, well sites denoted in yellow were those labeled '< MRL' in the UCMR 5 dataset since there are no 0 values in the UCMR 5 dataset.

Furthermore, I used resources from the water board to visualize these results in proportion to other shapefiles. A second set of data was used to analyze critical variables. In March 2019, an order from the State Water Resources Control Board identified a list of facilities following water code section 13267, which required facilities that have accepted, stored, or used material that may contain per- and polyfluoroalkyl substances (PFAS) (California Water Board Opendata. 2024). A requirement for investigative reporting to deduce the presence or absence of PFAS at these facilities led to much of the current UCMR data. This list included airports, chrome plating facilities, Department of Defence facilities, landfills – active solid waste municipal, publicly owned treatment works facilities, refineries, and bulk terminals. Using a map of the locations and information of facilities, I deduced where these facilities occurred in relation to wells contaminated with PFOA. In this analysis, I have decided to exclude variables that may impact the transportation of PFOA, such as watershed connectivity, soil structure, and other geologic traits that may affect movement due to time constraints and data availability.

Similarly, I took shapefiles of the regional water board boundaries from the California State Water Board website to visualize well sites contaminated with PFOA with governing agencies. I decided to use this visualization to see if there were actions each waterboard could take to address PFOA contamination within its boundaries. There are nine semi-autonomous Regional Boards comprised of seven part-time Board members appointed by the Governor and confirmed by the Senate (California State Water Board 2020). These boundaries are based on watersheds and water quality requirements due to the differences in climate, topography, geology, and hydrology within each watershed. These boards make critical decisions for their region concerning water quality, including setting standards, issuing requirements, determining compliance, and taking enforcement actions.

Exploratory Data Analysis

I used R programming with the original UCMR 5 dataset to run some exploratory data analysis. These analyses were done to understand further distributions of samples within the UCMR 5 in terms of the level of contamination. Since I used ArcGIS to understand spatially where contamination was occurring, I also wanted to understand to what extent contamination was occurring in certain areas. To do this, I created graphs of distribution frequency of results by excluding values marked as below the MRL. I also found the number of samples above and below the MCL and the PWS with the highest number of samples above the MCL by manipulating this dataset.

RESULTS

In total, 107 of the 2324 samples were above the MCL. Analysis through R revealed that 44 Public Water Systems had samples over the MCL in UCMR 5 (Table 1). While most PWS had

1 or 2 samples above the MCL, the City of Fresno, City of Clovis, Santa Clarita Valley W.A. – Valencia Divis, and Rancho California Water District had the highest number of samples above the new MCL. It's worth noting that the City of Fresno, with 180 samples, had the highest number of samples taken. Similarly, the Rancho California Water District had 69 samples, and the City of Clovis had 66. Santa Clarita had fewer samples taken, with 11, but still a high number of them were over the MCL. The only outlier with this trend was the City of Tulare PWS, which had 38 samples taken, but none were above the MCL (or MRL).

Table 1: Public Water Systems with Samples Above New MCL (0.004 ug/L)

PWS ID	Number of Samples Above New MCL	PWS Name
CA1010007	18	CITY OF FRESNO
CA1010003	7	CITY OF CLOVIS
CA1910240	7	SANTA CLARITA VALLEY W.A.-VALENCIA DIVIS
CA3310038	7	RANCHO CALIFORNIA WATER DISTRICT
CA1910125	4	PICO WD
CA3610005	4	LAKE ARROWHEAD CSD
CA3610112	4	HELENDALE COMMUNITY SERVICE DISTRICT
CA5610008	4	PLEASANT VALLEY MUTUAL WATER CO
CA1510003	3	CWS - BAKERSFIELD
CA1910211	3	LIBERTY UTILITIES - BELLFLOWER-NORWALK
CA3310026	3	NUEVO WATER COMPANY
CA1910017	2	SANTA CLARITA VALLEY W.A.-SANTA CLARITA
CA1910140	2	RUBIO CANON LAND & WATER ASSOCIATION
CA1910152	2	SOUTH GATE-CITY, WATER DEPT.
CA1910160	2	TRACT 349 MUTUAL WATER CO.
CA2710004	2	CAL AM WATER COMPANY - MONTEREY
CA3410010	2	Cal Am - Suburban Rosemont
CA3410017	2	CALAM - PARKWAY
CA3410045	2	CALAM - ARDEN
CA3610014	2	COLTON, CITY OF
CA4510005	2	CITY OF REDDING
CA0110003	1	CALIFORNIA WATER SERVICE - LIVERMORE

CA0900659	1	SIERRA TAHOE MAIN LODGE
CA1010339	1	CALIFORNIA STATE UNIVERSITY FRESNO
CA1900046	1	PETER PITCHESS HONOR RANCHO DETN. CTR
CA1910024	1	GSWC - CLAREMONT
CA1910028	1	CRESCENTA VALLEY CWD
CA1910049	1	HUNTINGTON PARK-CITY, WATER DEPT.
CA1910126	1	POMONA - CITY, WATER DEPT.
CA2310003	1	UKIAH, CITY OF
CA2410001	1	CITY OF ATWATER
CA3010062	1	CITY OF GARDEN GROVE
CA3310025	1	NORCO, CITY OF
CA3310046	1	FARM MUTUAL W.C. (THE)
CA3410020	1	CITY OF SACRAMENTO MAIN
CA3610024	1	HESPERIA WD
CA3610034	1	ONTARIO MUNICIPAL UTILITIES COMPANY
CA3610037	1	REDLANDS CITY MUD-WATER DIV
CA3610038	1	RIALTO, CITY OF
CA3610043	1	GOLDEN STATE WATER CO - BARSTOW
CA3610055	1	YUCAIPA VALLEY WATER DISTRICT
CA4010002	1	ATASCADERO MUTUAL WATER CO
CA4910012	1	SONOMA, CITY OF
CA5410010	1	PORTERVILLE, CITY OF

We can observe the visual representation of the spatial distribution of all public supply wells in California in relation to Public Water Systems sampled for PFOA (Figure 1). Here, PWS with samples above the MCL are denoted in red, while those under the MCL are denoted in yellow. Since the MCL and MRL are now the same (0.004 ug/L), those in yellow were marked as '< MRL' in the UCMR 5 dataset. Spatially, PWS sampled for PFOA were concentrated in the Bay Area, Central Valley, and greater Los Angeles area. There are some outliers, as seen in the PWS sampled near Chico, Sacramento, Atascadero, and the Lake Tahoe area. However, many wells are not sampled in Northern California and Eastern California, even in some of the outskirts of Southern California near the border of Arizona.

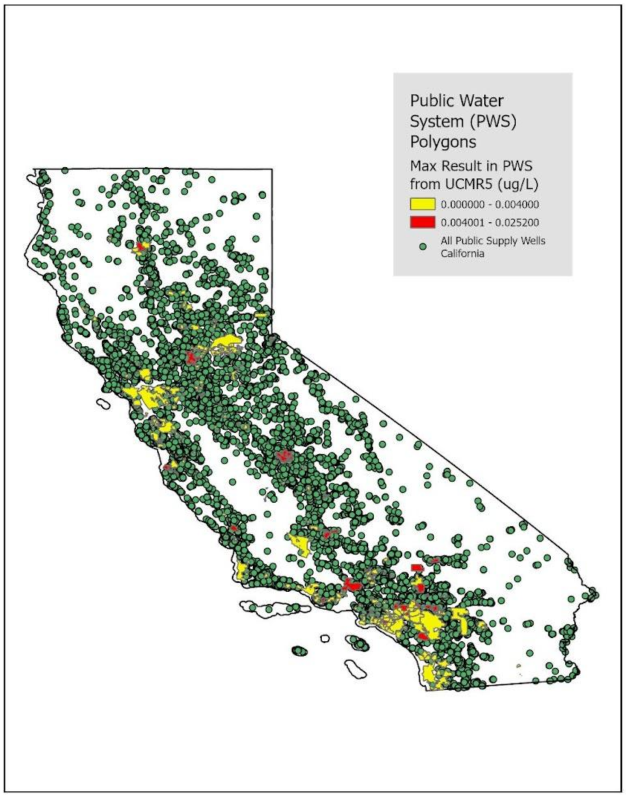

Figure 1: Public Water System Polygons in Relation to all Public Supply Wells (US EPA, California State Water Board).

Figure 2 provides context for the distribution of public water systems in relation to sites with investigative notices. These sites, as mentioned before, Refineries and Bulk Terminals, Publicly Owned Treatment Works, Landfills, Department of Defense Facilities, Chrome Plating Facilities, and Airports, previously used PFOA in practice. As shown here, while most investigative sites correlate to areas tested for PFOA, there are areas of Northern California and Eastern California where there are both, as mentioned above, well sites without sampling and investigative sites in these areas. Investigative sites pose risks to drinking water, and even with the entire dataset, it is unclear whether these wells will be sampled.

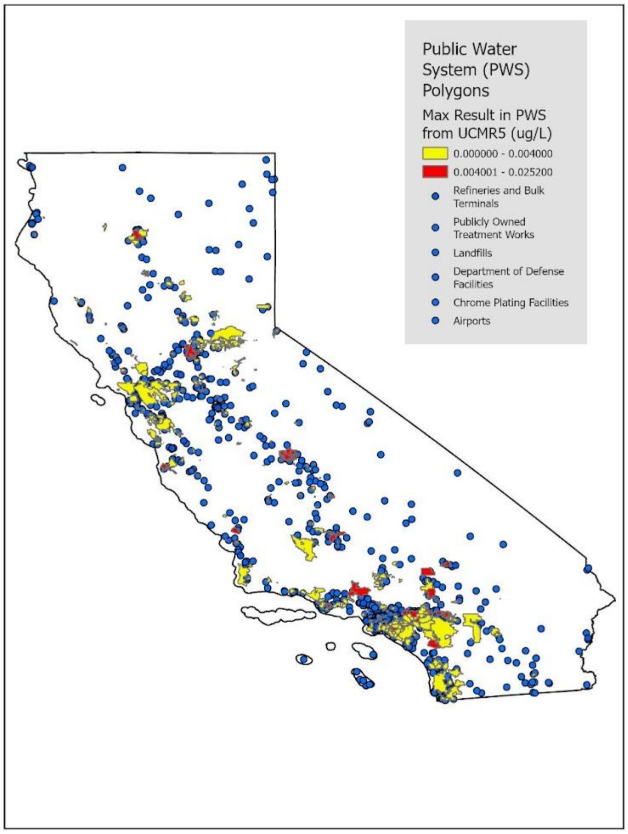

Figure 2: Public Water Systems in Relation to Sites with Investigative Notices (US EPA, California State Water Board).

A small relationship exists between regional water board boundaries and public water systems tested for PFOA (Figure 3). The Lahontan, Colorado River, and North Coast regional boards are severely underrepresented in the UCMR 5 dataset. Many public water systems with PFOA samples were within the San Francisco Bay, San Diego, Santa Ana, Los Angeles, and Central Valley regional board boundaries.

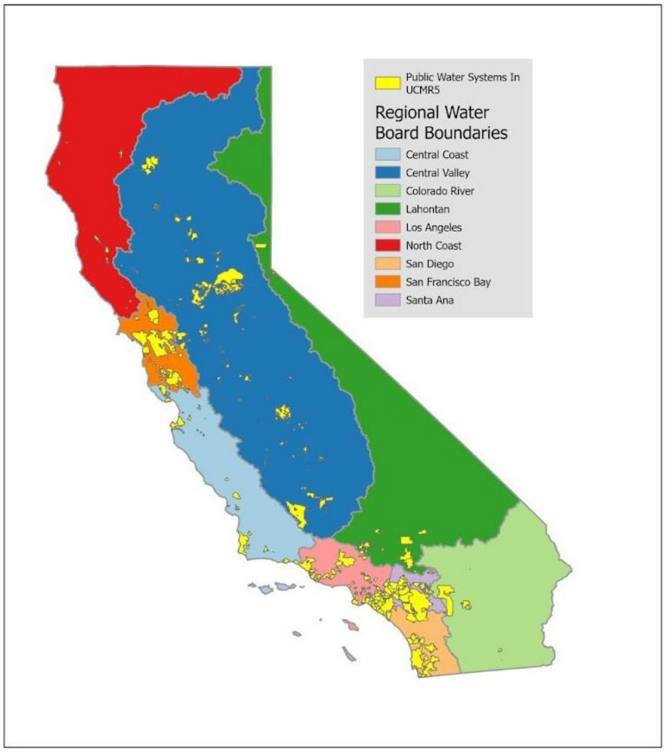

Figure 3: Public Water Systems in Relation to Regional Board Boundaries (US EPA, California State Water Board).

DISCUSSION

Understanding PFOA's spatial distribution in California water systems is crucial for directing monitoring efforts toward under-researched or at-risk areas. PFOA's spatial distribution analysis reveals distinct patterns that align with urban areas and industrial facilities. This trend mirrors previous studies where higher concentrations of PFAS were found in proximity to industrial facilities and urban areas (Hu et al. 2016, Antonopoulou et al. 2024). Interestingly, this analysis uncovered a potential correlation between the number of samples taken in a Public Water System and the likelihood of samples exceeding the Maximum Contaminant Level. This finding underscores the significance of monitoring efforts in rural communities that may have been overlooked in previous studies.

Samples Exceeding the MCL

Out of the 2324 samples analyzed, 107 samples surpassed the MCL outlined in the Fifth Unregulated Contaminant Monitoring Rule, distributed across 44 distinct Public Water Systems. While most systems recorded 1-3 samples exceeding the MCL, the City of Fresno Public Water System presented 18 samples surpassing the new MCL. Upon spatial analysis, it remains ambiguous whether heightened industrial activity or other risk factors in this vicinity contributed to the elevated proportion of samples exceeding the MCL. It is plausible, however, that this discrepancy is primarily due to the substantial sampling effort undertaken by the City of Fresno PWS, which conducted 180 samples, significantly more than other systems in the dataset. This prompts inquiry into whether increased sampling efforts might yield a higher frequency of samples surpassing the MCL. There appears to be a marginal trend indicating that PWS with more extensive monitoring tend to exhibit more samples exceeding the MCL; however, the City of Tulare PWS presents an anomaly in this trend. Despite 38 samples being conducted, no PFOA contamination was detected. The complete dataset will make it clearer whether intensified monitoring efforts correlate with a higher incidence of samples surpassing the MCL.

Geographic Analysis

The spatial analysis conducted on contaminated well sites reveals distinct geographical patterns, emphasizing areas with heightened concentrations of PFOA. Significant hotspots correspond with California's most populous urban regions, including the Bay Area, Central Valley, and the greater Los Angeles area. However, examining factors influencing elevated PFOA concentrations in urban areas is complicated by the uneven distribution of sampled Public Water Systems (PWS) within these locales. Previous maps indicate a limited geographic spread of PWS samples monitoring for PFOA, leaving vast swathes of California unmonitored. This sampling bias constrains our ability to discern clear patterns in rural areas and conduct further analyses on factors influencing concentrations in these regions.

Nonetheless, these results align with other studies where higher concentrations of PFOA were detected in urban water systems (Antonopoulou et al. 2024). An interplay of factors could affect why these patterns exist, such as increased rates and proximity of industrial activities, population density, and land use patterns.

Examining Risk Factors

When juxtaposing the spatial analysis of tested sites with the results obtained from the risk variables, a clear presence of factors associated with PFAS contamination emerges in these urban areas. These findings are consistent with similar PFAS maps across the United States, as demonstrated by the Environmental Working Group's mapping initiatives utilizing UCMR 3 data. These maps reveal identifiable risk factors in these areas, and past studies have established a strong correlation between investigative sites and well contamination (Hu et al. 2016). Similar patterns are observed in states like Michigan and Illinois, where contamination of drinking water is more prevalent in larger cities such as Detroit and Chicago. However, this pattern diverges when observing elevated concentrations in places such as Bakersfield and Fresno within the Central Valley of California. While one explanation for this deviation could be attributed to industrial activities, another aspect not extensively explored in this research is the utilization of PFAS in agricultural pesticides. The dispersal and contamination of soils with PFAS are significant factors contributing to the movement of PFAS in water systems and human exposure (Andersen et al. 2024). Another contributing factor to this trend could be the flow of PFOA in water systems, as evidenced by its detection downstream from 16 Southern and Central California wastewater treatment plants (Desgens-Martin et al. 2023). These factors, whether acting in tandem or separately, underscore the dynamic nature of PFOA contamination and emphasize the need for regulatory agencies to implement more comprehensive monitoring strategies.

Regional Water Board Assessment

To emphasize the significance of the involvement of Regional Water Boards in PFAS testing, the map highlights deficiencies in each agency's current monitoring objectives. As previously noted, ensuring compliance with monitoring protocols typically falls on regional water boards. While the EPA ultimately regulates health advisories for PFOA in drinking water (State Water Resources Control 2024), it is the regional water boards that are entrusted with issuing permits and conducting more vigilant water quality monitoring. The limited testing within the boundaries of the North Coast and Lahontan regional board jurisdictions suggests a need for these boards to reconsider their approach to PFOA monitoring within their respective counties.

Limitations

The datasets employed in this analysis faced notable constraints, primarily stemming from the sampling process of UCMR 5. Firstly, exclusively relying on public well sites inherently excluded numerous communities served by community or private wells, thereby limiting the scope of our investigation. There are many community and private wells located in rural areas that were unresearched in this study. This made it difficult to analyze whether the occurrence of PFOA in water systems in urban areas resulted from increased monitoring in these urban zones or was indicative of the environmental impacts associated with urbanization. This was further impacted by the incomplete dataset, meaning assumptions had to be made to analyze the results, and once all the results have been published, other patterns may be revealed. Moreover, the incomplete nature of the UCMR 5 dataset poses an additional limitation, confining the spatial analysis to areas that may already exhibit a predisposition to contamination.

Furthermore, as discussed in the preceding sections, the monitoring protocol associated with the UCMR datasets imposed restrictions on the comprehensiveness of data collection and recording. This led to specific values being aggregated under the designation '< MRL,' a practice that curtails the granularity of the dataset. Since technology limits the ability of researchers to detect PFOA under the MRL, no definitive zeros could be established. This meant that in areas sampled with no results, there was still the possibility of some contamination. Along with this, it made it difficult to analyze the impacts of risk factors on contamination levels, as not having a baseline meant there was no control for this analysis. Along the same lines for the risk analysis, solely focusing on geographic proximity left out other essential considerations in the flow of contaminants in water bodies.

Future Directions

Following the limitations of this study leads to interesting pathways for future research. A more comprehensive analysis of the impact on geological characteristics, proximity, and flow patterns could be used to understand how upstream risk factors could impact surrounding communities. Factors affecting the movement of contaminants in watersheds could impact how distantly industrial byproducts may impact communities (Rafiei and Nejadhashemi 2023). In addition to this, with the wide range of uses for PFAS, there are thousands of other routes of exposure not explored in this research. The impacts of pesticides and wildfires are one such example, but further analysis could be done on each of these factors to understand how they may intersect to increase the occurrence of PFOA in drinking water (Solomon et al. 2021). Lastly, a more detailed analysis of the exact well sites contaminated could reveal more information about how proximity and policy protocols impact contamination in communities.

Broader Implications

Identifying hotspots for PFOA allows policymakers and environmental agencies to prioritize remediation efforts and proactively implement preventive measures. These insights contribute to a broader understanding of PFAS contamination, facilitating informed decision-making and effective resource allocation in addressing this environmental challenge. Integrating such insights into our findings is invaluable for shaping regulatory measures and fostering collaborative initiatives with industry to mitigate environmental impact. This information not only enhances our understanding of the sources of contamination but also provides a foundation for developing targeted strategies to curtail further ecological degradation. As we move forward, regulatory frameworks and mitigation efforts must consider the full aspect of contaminants in water systems, emphasizing the importance of collaboration between environmental agencies and industry to achieve sustainable and practical solutions to mitigate public health risks.

ACKNOWLEDGEMENTS

This undergraduate thesis was a part of the Environmental Science program in the Environmental Science, Policy, and Management Department of UC Berkeley. I thank my instructors, Patina Mendex and Jessica Craigg, and my workgroup for their continued guidance through the writing process, suggesting analysis approaches, and supporting me through this new and exciting research journey. Further, I want to express my heartfelt gratitude to my mentor, Dr. Clare Pace. Your expertise and wisdom were both inspiring and instrumental in shaping the path of my research and my future goals in environmental health. To my roommates, Hayley Lai and

Phyllis Lam, thank you for putting up with my late-night thesis questions and forever motivating and inspiring me to reach higher than I thought possible. Lastly, to my friends and family, your continued love, support, and encouragement have pushed me to pursue my dreams and made me realize my potential was far greater than I ever imagined.

REFERENCES

A Timeline of US Federal Actions on PFAS. 2022. Apex AP. https://apexcos.com/blog/a-timeline-of-us-federal-actions-on-pfas/.

Andersen, H. R., P. Grandjean, K. M. Main, T. K. Jensen, and F. Nielsen. 2024. Higher serum concentrations of PFAS among pesticide exposed female greenhouse workers. International Journal of Hygiene and Environmental Health 255:114292.

Antonopoulou, M., A. Spyrou, A. Tzamaria, I. Efthimiou, and V. Triantafyllidis. 2024. Current state of knowledge of environmental occurrence, toxic effects, and advanced treatment of PFOS and PFOA. Science of The Total Environment 913:169332.

Belitz, K., N. M. Dubrovsky, K. Burow, B. C. Jurgens, and T. John. 2003. Framework for a ground-water quality monitoring and assessment program for California. Water-Resources Investigations Report.

Brennan, N. M., A. T. Evans, M. K. Fritz, S. A. Peak, and H. E. von Holst. 2021. Trends in the Regulation of Per- and Polyfluoroalkyl Substances (PFAS): A Scoping Review. International Journal of Environmental Research and Public Health 18:10900.

Desgens-Martin, V., W. Li, T. Medina, and A. A. Keller. 2023. Estimated Influent PFAS Loads to Wastewater Treatment Plants and Ambient Concentrations in Downstream Waterbodies: Case Study in Southern and Central California. ACS ES&T Water 3:2219–2228.

Domingo, J. L., and M. Nadal. 2019. Human exposure to per- and polyfluoroalkyl substances (PFAS) through drinking water: A review of the recent scientific literature. Environmental Research 177:108648.

Emerging Contaminants (EC) in Small or Disadvantaged Communities Grant (SDC): Overviews and Factsheets. 2022. U.S. Environmental Protection Agency. https://www.epa.gov/dwcapacity/emerging-contaminants-ec-small-or-disadvantaged-communities-grant-sdc.

Fenton, S. E., A. Ducatman, A. Boobis, J. C. DeWitt, C. Lau, C. Ng, J. S. Smith, and S. M. Roberts. 2021. Per- and Polyfluoroalkyl Substance Toxicity and Human Health Review: Current State of Knowledge and Strategies for Informing Future Research. Environmental toxicology and chemistry 40:606–630.

Fifth Unregulated Contaminant Monitoring Rule: Data and Tools. 2021. U.S. Environmental Protection Agency. https://www.epa.gov/dwucmr/fifth-unregulated-contaminant-monitoring-rule.

California State Water Resources Control Board. GAMA - About. 2023. https://www.waterboards.ca.gov/water_issues/programs/gama/about.html.

Hu, X. C., D. Q. Andrews, A. B. Lindstrom, T. A. Bruton, L. A. Schaider, P. Grandjean, R. Lohmann, C. C. Carignan, A. Blum, S. A. Balan, C. P. Higgins, and E. M. Sunderland. 2016. Detection of Poly- and Perfluoroalkyl Substances (PFASs) in U.S. Drinking Water Linked to Industrial Sites, Military Fire Training Areas, and Wastewater Treatment Plants. Environmental Science & Technology Letters 3:344–350.

Kurwadkar, S., J. Dane, S. R. Kanel, M. N. Nadagouda, R. W. Cawdrey, B. Ambade, G. C. Struckhoff, and R. Wilkin. 2022. Per- and polyfluoroalkyl substances in water and wastewater: A critical review of their global occurrence and distribution. Science of The Total Environment 809:151003.

Kwiatkowski, C. F., D. Q. Andrews, L. S. Birnbaum, T. A. Bruton, J. C. DeWitt, D. R. U. Knappe, M. V. Maffini, M. F. Miller, K. E. Pelch, A. Reade, A. Soehl, X. Trier, M. Venier, C. C. Wagner, Z. Wang, and A. Blum. 2020. Scientific Basis for Managing PFAS as a Chemical Class. Environmental Science & Technology Letters 7:532–543.

Pace, C., C. Balazs, K. Bangia, N. Depsky, A. Renteria, R. Morello-Frosch, and L. J. Cushing. 2022. Inequities in Drinking Water Quality Among Domestic Well Communities and Community Water Systems, California, 2011–2019. American Journal of Public Health 112:88–97.

Per- and Polyfluoroalkyl Substances (PFAS) Investigation Sites - Overview. 2024. California Water Board Open data. https://gispublic.waterboards.ca.gov/portal/home/item.html?id=4feba1766c224dc99eadea06ef3bd019.

Per- and Polyfluoroalkyl Substances (PFAS): Reports and Assessments. 2021. U.S. Environmental Protection Agency. https://www.epa.gov/sdwa/and-polyfluoroalkyl-substances-pfas.

PFAS: Per- and Polyfluoroalkyl Substances Drinking Water Systems. 2024. State Water Resources Control Board.https://www.waterboards.ca.gov/drinking_water/certlic/drinkingwater/pfas.html.

Rafiei, V., and A. P. Nejadhashemi. 2023. Watershed scale PFAS fate and transport model for source identification and management implications. Water Research 240:120073.

Regional Water Quality Control Boards in California. 2020. California State Water Board. https://www.watereducation.org/aquapedia/regional-water-quality-control-boards-california.

Schaider, L. A., L. Swetschinski, C. Campbell, and R. A. Rudel. 2019. Environmental justice and drinking water quality: are there socioeconomic disparities in nitrate levels in U.S. drinking water? Environmental Health 18:3.

Solomon, G. M., S. Hurley, C. Carpenter, T. M. Young, P. English, and P. Reynolds. 2021. Fire and Water: Assessing Drinking Water Contamination After a Major Wildfire. ACS ES&T Water 1:1878–1886.

Veasy, P., J. Dean, and S. Goldberg. 2022. California Steps Up Its Investigations and Permitting of PFAS. https://www.downeybrand.com/legal-alerts/california-steps-up-its-investigations-and-permitting-of-pfas/.

Wee, S. Y., and A. Z. Aris. 2023. Revisiting the "forever chemicals", PFOA and PFOS exposure in drinking water. npj Clean Water 6:1–16.