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# Disparities in drinking water quality: evidence from California

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## ABSTRACT

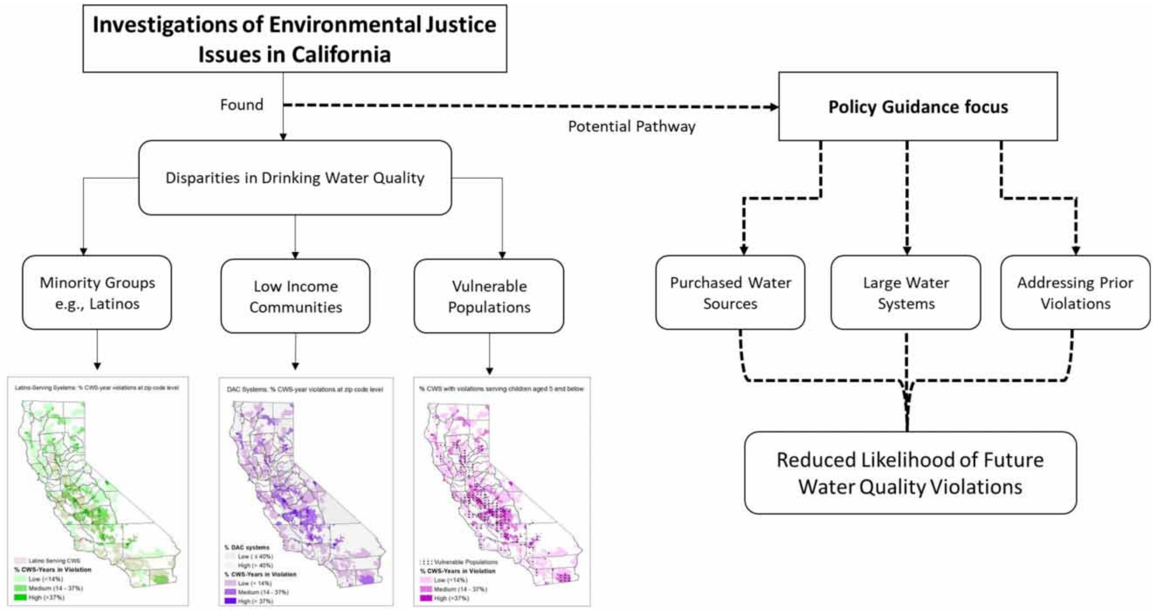
Reducing disparities in drinking water quality is a state-level priority in California, yet targeting communities for assistance is hindered by the lack of empirical evidence regarding populations disproportionately affected. The study addresses this gap by analyzing drinking water quality violations and identifying the types of communities disproportionately burdened by water contaminants. Using a sample of 1,710 Community Water Systems (CWSs) and probit regression models, we analyzed the likelihood of violation as a function of low-income, minority groups, and vulnerable populations. Results indicate that environmental justice concerns are prevalent. Low-income communities and minority groups (Hispanics and non-Whites) face greater likelihood of water quality violations. Low-income communities are 1.77% more likely to have any health-related violations. Severely disadvantaged communities face greater likelihood (3.44%) of water quality violations. Tribal water systems are 2% more likely to violate the Total Coliform Rule. Children aged five and under are 3% more likely to be exposed to health-based water quality violations. Failure to address prior violations leads to greater likelihood (38.94%) of future violations, while large utility systems and purchased water sources have the propensity to reduce violations. Overall, these findings can guide policy decisions to prioritize assistance to communities disproportionately impacted by poor water quality.

**Key words:** Community Water Systems, Environmental justice, Violation, Water quality

## HIGHLIGHTS

- About 0.3–3.0 million populations are served by noncompliant CWSs each year.
- Failure to address previous water contaminant violations has a high marginal effect.
- Tribal water systems made up 3.9% of CWS observations but incurred 10.7% of violations.
- Small CWSs are particularly burdened by shifting regulations due to capacity constraints.
- Latinos and African Americans are associated with nitrate and arsenic violations, respectively.

## GRAPHICAL ABSTRACT




## INTRODUCTION

The inequity in access to safe drinking water remains a public health concern nationwide (Mueller & Gasteyer, 2021). Each year, over 7% of Community Water Systems (CWSs) incur health-based violations (Allaire *et al.*, 2018). In California, ensuring safe drinking water for communities statewide is a prominent challenge (Hanak *et al.*, 2014). The growing awareness of inadequate access, especially for Disadvantaged Communities (DACs), has elevated water quality issues at the state level. Low-income and minority communities might face disproportionate exposure to impaired drinking water (Su *et al.*, 2009; Schaider *et al.*, 2019). Impaired drinking water in California is influenced by contaminated groundwater and the prevalence of small systems in rural and/or unincorporated areas that lack technical, managerial, and/or financial capacity.

Groundwater in many parts of the state contains naturally occurring contaminants (arsenic and uranium) and human-induced pollutants (particularly nutrient loss and transport from agricultural production). The vast majority of CWS (83%) serving disadvantaged unincorporated communities in the San Joaquin Valley (SJV) rely on groundwater sources often facing nitrate contaminant challenges (London *et al.*, 2021). Water treatment technologies for these contaminants can be expensive to construct and maintain for small water systems that lack appropriate economies of scale. Meanwhile, 1.2 million people depend on domestic wells (Johnson & Belitz, 2015) for water supplies. Many rural water systems, which are mostly small CWS, have been noncompliant for 3 years or more (Hanak *et al.*, 2019). Persistent violations are especially common in rural and agricultural areas. For example, about half of non-compliant water systems in California are in the SJV, where a higher proportion of households are estimated to have low income. Statewide, over 30% of California's households are in DACs (Flegal *et al.*, 2013).

Additionally, increasing population growth presents a special challenge to the need for safe and reliable drinking water supplies. Population growth has outpaced the capacity of CWS to meet the growing demand for safe water supplies. 85% of CWS serves only 6% of California's population (SWRCB, 2017). Drinking water provision in California is highly fragmented. Nearly 94% of the state population is served by only 15% of CWS (SWRCB, 2017), which are larger systems and serve more than 10,000 people. In Los Angeles County alone, there are 205 CWSs, although 38% of the county's population is served by a single CWS– the Los Angeles Department of Water and Power. CWS ownership type could be public or private. Statewide, privately owned CWSs account for about 16% of the populations served in California (Pannu *et al.*, 2018).

The State Water Board has primary responsibility for enforcing safe drinking water standards in California. However, water systems serving fewer than 200 connections are regulated in some counties by a Local Primacy Agency (LPA). A total of 7,403 Public Water Systems (PWSs) are regulated by the Division of Drinking Water and LPA as of 2019. Of these, 3,440 small PWSs in 30 counties are overseen by an LPA (SWRCB, 2019). In 2012, the state legislature passed the Human Right to Water Act (AB 685), which recognizes that 'every human being has the right to safe, clean, affordable, and accessible water.' Additional laws (AB 2501 and AB 2541) passed in 2018 increased the State Water Board's ability to force system consolidation or support communities where consolidation is not feasible (AB 2501) and expand access to the Drinking Water State Revolving Fund (DWSRF) for Severely Disadvantaged Communities (SDACs) (AB 2541). Assistance to struggling communities is offered as state bonds and the DWSRF among other federal programs such as the Safe and Affordable Drinking Water Fund (SB 200), established in 2019. While financial assistance may be available to struggling CWSs, it is often limited to infrastructure improvements.

Despite efforts by the SWRCB to regulate water systems and provide some financial support for water infrastructure development, the issue of safe drinking water supplies in the region remains a challenge. The 2019 compliance report from SWRCB shows a total of 2,309 violations of the National Drinking Water Regulations. Over 91% of the observed violations were associated with small PWSs. In 2018, over 1 million people were estimated to lack access to safe water in California (Pannu, 2018). Substantial investment is needed to correct this situation – approximately $30–160 million annually (Hanak *et al.*, 2014). State-level policy efforts in California seek to address drinking water disparities. Yet, the full scope of this challenge is unknown. At present, California lacks a full understanding of the populations that lack access to safe water and the spatial distribution of violations. In-depth knowledge is needed to improve compliance and achieve the human right to water in California.

Few studies in the U.S. address disproportionate exposures to drinking water violations by low-income (Stone *et al.*, 2007; Balazs *et al.*, 2012), minority groups (Balazs *et al.*, 2011; Schaider *et al.*, 2019), and vulnerable populations. Previous research is limited by a small sample size and aggregate units of analysis beyond the water system level. This study makes a unique contribution to the literature on social disparities in drinking water quality by integrating indicators for low-income groups, minorities, and vulnerable populations at the CWS level of data analysis (the first of its kind). Across the U.S., water utilities are not required to report the demographics of their service areas and this result in difficulty in linking drinking water quality to the socioeconomic and demographic characteristics of communities. Notably, this study develops demographic information at the CWS level.

In summary, this study addresses knowledge gaps regarding environmental justice[1] and disparate exposure to impaired water quality by (i) analyzing trends in violations of drinking water quality standards in California, (ii) identifying whether low-income, minority, and/or vulnerable populations bear disproportionate burdens of water quality violations, and (iii) examining the inclusion of relevant control variables such as housing density (rural vs. urban), utility size (small, medium, and large), and water source type (groundwater, surface water, and

[1] Environmental justice, as applied to this study, characterizes the fairness of the water quality impact of contaminant violations regardless of race, income, or color through the enforcement of policies and regulations.

purchased). An in-depth understanding of the social disparities, funding capacity, and impact of environmental justice is crucial to sustainable water service development (Marques *et al.*, 2015). This work will not only bridge the existing knowledge gap but also provide a potential pathway for water decision-makers to plan toward safe and sustainable drinking water supplies. With limited state funding to support small water utilities, it is imperative that policy guidance focuses on optimizing water quality benefits by targeting the best use of financial resources and sustainability co-benefits built into water policy decisions. The overarching goal of this study is to inform the prioritization of state-level assistance, particularly as California seeks to promote cost-effective solutions for communities struggling with persistent water quality concerns.

The organization of the paper follows a concise review of related literature, where evidence of prior research contributions and limitations about environmental justice are discussed. The review emphasizes case studies specific to California in addition to relevant research works with a nationwide or international outlook. The methodology follows with a detailed description of the dataset, water quality violations reported to the United States Environmental Protection Agency (U.S. EPA), water system indicators, socioeconomic characteristics, and model description. The final sections of the article present and discuss the results, with a high-level summary of key findings as the conclusion.

## LITERATURE REVIEW

Evidence from prior studies suggests that low-income (Stone *et al.*, 2007; Switzer & Teodoro, 2017), rural (Guerrero-Preston *et al.*, 2008; Delpla *et al.*, 2015; Jepson & Vandewalle, 2016), and minority communities (Balazs *et al.*, 2011; VanDerslice, 2011; MacDonald Gibson *et al.*, 2014; Pierce & Jimenez, 2015; Ranganathan & Balazs, 2015; Allaire *et al.*, 2018; Conroy-Ben & Richard, 2018; McDonald & Jones, 2018) face disproportionate exposure to drinking water contamination. A statewide research by the Environmental Justice Coalition for Water in 2005 examined how the lack of safe drinking water access disproportionally affects minority communities (Deen *et al.*, 2005). The authors analyzed political, social, and economic trends within low-income and minority communities to understand the fundamental impacts of water-related environmental justice issues. Another research targeting water systems in the SJV shows that CWSs serving Latino communities struggle with higher levels of nitrate concentrations (Balazs *et al.*, 2011). Using 327 CWSs in central California and a hierarchical linear model, the association between nitrate levels in drinking water and demographics at the census block group level were analyzed. Findings suggest that utilities serving larger proportions of Latino residents tend to have higher nitrate concentrations. Most of the aquifers in the SJV face the challenge of nitrate contamination (Moore *et al.*, 2011). An analysis of a household survey administered in four CWSs found household water users exposed to high levels of nitrate contamination, a lack of accurate water quality information, and water cost that exceeds national levels. In a review article, Alpers (2017) provides an overview of arsenic contamination in the Sierra Nevada in relation to historical gold mining and Fichot *et al.*, 2016 use a remote sensing methodological approach to monitor water quality in the San Francisco Bay. While observing spatial changes in water characteristics is relevant, it does not provide an in-depth understanding of the socioeconomic and demographic impacts that can guide water policy decisions efficiently.

Similar conclusions have been reached by research work on environmental justice of water quality nationwide. Stone *et al.*, (2007) found that residents disproportionately burdened by arsenic violations in Oregon had a median household income 20% lower than the state average. The research by McDonald & Jones (2018) also shows that minority groups face an increased likelihood of repeated water contaminant violations. Schaider *et al.*, (2019) using CWS characteristics data on 39,466 CWSs from 2010 to 2014 and county-level demographic data, analyzed nitrate concentrations and drinking water disparities in the U.S. Their findings show Hispanic residents are served by CWS with significant concentrations of nitrate contaminant above 5 mg/L. Another crucial knowledge gap is the limited research in the areas of water quality contaminant assessment and its impact on tribal nations. Tribal communities tend to face severe water quality (Eichelberger, 2010; Teodoro *et al*., 2018) and reliable access challenges that may be attributed to institutional and infrastructural constraints. Teodoro *et al*., (2018) examined the dynamics of enforcement (inspections) and compliance (with maximum contaminant level (MCL)) of both the Clean Water Act and Safe Drinking Water Act (SDWA) among tribal nations. Their results suggest increased drinking water quality violations and less rigorous inspections among tribal lands compared to nontribal lands. Conroy-Ben & Richard (2018) also analyzed the water quality disparities faced by Indian Country in the United States. Overall findings found violation disparities among tribal systems to be six times higher compared to the national average. An in-depth understanding of how each tribal nation is affected by drinking water contaminant types is fundamental to the development of community-specific solutions or interventions.

The international outlook on the environmental justice issues of water quality does not differ from findings from nationwide studies or state-level research. For instance, Delpla *et al*. (2015) reached a similar conclusion when they analyzed 593 rural municipalities and found that deprived municipalities have high levels of lead concentrations in drinking water because of the lack of water treatment applications. Conversely, affluent municipalities apply advanced treatment to improve the quality of lead-contaminated water. The results from this study established an unequal distribution of lead-impaired drinking water among rural communities. Guerrero-Preston *et al*. (2008) assessed the SDWA compliance of small, rural CWSs in Puerto Rico. Findings suggest that the majority of small, rural systems in Puerto Rico violated the SDWA during the 5-year study period.

While most of the previous research addressed the water quality concerns facing specific socioeconomic groups, there have been few case studies on the struggle for water justice. In the SJV, Pannu *et al*. (2018) examined the access to clean water by Disadvantaged Unincorporated Communities (DUCs). Results from their spatial analysis found that DUC residents in the SJV are served by small and often underperforming CWSs, leading to disparities in access to clean water. Valley-wide, 139 CWSs (out of 667) were determined to be out of compliance. The percent of racial/ethnic distribution of residents served by out-of-compliance CWSs was highest for Hispanic populations within DUC (63%) and incorporated communities (65%). Likewise, the research by Balazs & Ray (2014) found disparities in drinking water as driven by quality constraints and regulatory failures following changes in environmental and sociopolitical factors. Based on the critical review of previous research, we determined common limitations of prior studies to include: (i) the difficulty in analyzing water quality impacts at the zip code level because of demographic data constraints, (ii) the focus on a single water quality contaminant violation to the exclusion of other relevant MCL violations, (iii) the scale of analysis mostly confined to a small geographic area (especially with California, prior studies are highly concentrated in the SJV), and (iv) the omission of key variables. These limitations collectively present a snapshot of the water quality problem, which gives insufficient information to properly guide water policy decisions.

## METHODS

### Data

We assembled a panel dataset that includes 2,709 CWSs in California from 2000 to 2018. The regression sample data was restricted to CWSs that began reporting violation information to the EPA in 2000 or prior. CWSs are PWSs that provide year-round service for at least 25 people or 15 service connections. Within California, CWSs include systems overseen by the state of California and tribal governments. We compiled data at the CWS-year level on water quality violations, CWS characteristics, and socioeconomic variables. Violations and CWS characteristics data were obtained from the EPA's Safe Drinking Water Information System (SDWIS), while data on socioeconomic variables at the zip code level were gathered from the U.S. Census and the California State Finance Office. The final dataset for regression analysis makes up a balanced panel dataset of 1,710 CWSs (which translates into a total of 32,490 observations) that reported violation status throughout the study period 2000–2018.

### Water quality violations

Health-related violations are based on the National Primary Drinking Water Regulations. The year of violation occurrence is determined based on the start date of the compliance period. If no violations are reported in SDWIS each year for a CWS, we assume no violation occurred based on the premise that EPA requires states to report violation information. The following violation categories used in this study and are explained:

*Tier 1:* The EPA classifies Tier 1 violations as the most severe violation category since they pose an immediate risk to public health. Contaminants include total coliform, turbidity, nitrate, and nitrite.

*Nitrate:* This category includes nitrate and nitrite, which can pose acute health risks by limiting oxygen uptake in the blood, particularly in infants less than 6 months old.

*Arsenic:* Arsenic is a naturally occurring element and long-term exposure can cause cardiovascular disorders and an elevated risk of some cancers. Groundwater in the U.S. tends to have higher levels of arsenic than surface water (Frey & Edwards, 1997). The MCL for arsenic was considerably reduced from 50 μg/L in 1975 to 10 μg/L in 2001; final implementation was required by 2006.

*DBPs:* Disinfection byproducts (DBPs) are formed through reactions between disinfectant chemicals and organic material, often in a distribution system. Long-term exposure is associated with greater cancer risk and nervous system issues.

*Total coliform:* Total coliforms serve as an indicator for *Escherichia coli*, viruses, and parasites. Yet, total coliforms also include many types of bacteria that are not harmful to human health. Some bacteria, such as fecal coliform, can cause acute gastrointestinal illness, which can be deadly for vulnerable populations such as young children, seniors, and the immunocompromised. This category includes violations of the Total Coliform Rule (TCR), which can be separated into acute and nonacute violations. Acute violations include the detection of *E. coli*.

*SWTR + GWR*. The various contaminants are regulated under the Surface Water Treatment Rules (SWTRs) and the Ground Water Rule (GWR). The SWTRs address pathogens in surface water, including *Legionella*, *Giardia lamblia*, and *Cryptosporidium*. Meanwhile, the GWR is intended to control fecal contamination in the form of *E. coli*, Enterococci, and Coliphage. The GWR seeks to identify groundwater sources susceptible to fecal contaminants.

### Water system characteristics

Data on CWS characteristics are obtained from SDWIS and include system size, type of source water, and ownership type. Since SDWIS only reports the most recent year of system characteristics, these variables are time-invariant. Indicators of system size are based on population served; we follow EPA categorizations of small [3,300 people or less], medium [3,301–10,000], and large [over 10,000] (US Environmental Protection Agency, 2013). Source water indicates the primary source type – purchased water, surface water, or groundwater. Lastly, we classify CWS ownership as private or public. Public ownership includes the U.S. government (federal, state, or municipal) and Native American tribes. Some model specifications include an indicator of tribal ownership.

### Socioeconomic characteristics.

Socioeconomic characteristics are calculated for each CWS and include housing density and categories for income, race, ethnicity, and age. Demographic data at the zip code level were obtained from the U.S. decadal census for the years 2000, 2010, and 2014–2019 from the American Community Survey 5-year estimates. In order to calculate socioeconomic characteristics at the CWS level, we intersect zip code boundaries (O'Neill, 2012) and CWS service area boundaries. Shapefiles of service areas were obtained for CWSs that are regulated by the state of California (Tracking California, 2018) and tribal system boundaries (US Department of Interior – Indian Affairs, 2018). These intersections provided the portion of a given CWS service area that lies within a given zip code. The weighting of zip codes was done using population weighting. About 81% of CWSs serve a single zip code. The following socioeconomic characteristics are created:

*DACs:* They are defined by the California State Water Boards as having Median Household Income (MHI) less than 80% of the state wide annual MHI, (California Department of Water Resources (DWR) 2016). Median household income was obtained from the U.S. Census Bureau and was adjusted to 2017 dollars by using a consumer price index secured from the Bureau of Labor Statistics (BLS). Statewide MHI was obtained from the U.S. Census Bureau and the average value in real dollar terms was calculated for the years 2000–2018. Then, for each CWS, the average MHI at the CWS level was calculated for the years 2000–2018. If a CWS had an average MHI less than 80% of the statewide average adjusted to 2017 dollars, it received a DAC designation.

*SDACs:* They are defined by the California State Water Boards as having MHI less than 60% of the state median.

*Race categories:* Percentage of the CWS population that is non-White or Native American and African American. Non-White is calculated as 1 minus the percentage of the White population.

*Ethnicity:* Percent of the CWS population that is Hispanic.

*Housing density:* This socioeconomic characteristic is used to show the extent to which an area is rural, suburban, or urban.

*Age categories:* Defines the percentage of the CWS population served that are young children (under the age of five) or seniors (65 years or older).

## Model description

We analyze water quality violations of 1,710 CWSs from 2000 to 2018 to identify which contaminants are particularly prevalent across California. In addition, we assess if minority and/or vulnerable groups bear a greater burden of impaired water quality. Vulnerable populations, such as young children and seniors, can be especially prone to health impacts if exposed to certain contaminants. A regression sample of 1,710 CWSs is used following observed health-related quality violations from 2000 to 2018. Probit regression models examine the likelihood of violations as a function of the demographics of CWS service area. The likelihood of a water quality violation occurring at a given CWS in each year is modeled as follows:

$$Pr(V_{it} = 1|X) = \Phi(\alpha_{it} + \beta_1 D_i + \beta_2 X_i + \beta_3 V_{it-1} + \gamma_t + \varepsilon_{it}) \tag{1}$$

The probability of a violation is estimated as a function of water system characteristics ($X_i$), vector of socioeconomic characteristics within the service area of each CWS ($D_i$), water quality violations from the previous period ($V_{it-1}$), fixed year effects($\gamma_t$), and the error term ($\varepsilon_{it}$). System characteristics include system size, raw water source, and ownership type. Socioeconomic variables include an indicator for DACs, housing density, and categories for race, ethnicity, and age. Interactions between categories for income and race as well as income and age are included in some model specifications. Models are specified for several violation types – total violations, total coliform, SWTR + GWR, nitrate, arsenic, and DBPs. Environmental justice and vulnerability concerns might differ across contaminants. We estimate average marginal effects (ME).

### Variable selection

Covariate selection relied on theory, based on a literature review. Utility size can show the capacity to provide safe water and the types of regulations faced by a given CWS. It is hypothesized that larger utilities have greater technical, managerial, and financial capacity to comply with regulations (Government Accountability Office, 1990). Water source is expected to be associated with violation occurrence, although the association likely differs across violation types. Purchased water might be less likely to incur SDWA violations, since larger utilities that supply wholesale water might have greater ability to comply with SDWA regulations (Wallsten & Kosec, 2008). Groundwater sources can be impaired by improper wastewater disposal, agrochemical pollutants (Dziegielewski & Bik, 2004), and naturally occurring contaminants such as arsenic (US Environmental Protection Agency, 1999) and radionuclides. Meanwhile, surface water sources can be prone to pathogens and higher concentrations of organic material. Ownership type – private or public – might influence compliance. For example, in California, large private utilities that are investor-owned face state regulation of water rates and oversight of finances, which could motivate improved compliance with SDWA regulations. Among public systems, there are documented concerns regarding higher violation occurrences at systems owned by Native American tribes (US Environmental Protection Agency, 2013). Socioeconomic variables include income indicators (DACs and SDACs), housing density, and categories for race, ethnicity, and age. It is expected that CWS with lower-income service areas will have fewer financial resources, which can mean less capacity to achieve compliance. The housing density is anticipated to have a negative association since rural utilities might be more likely to violate it. It is also anticipated that utilities serving greater shares of minority populations will be more likely to incur violations.

### Limitations

The research investigations described in this paper focus on analytical procedures that seek to establish optimal policy guidance for addressing the social disparities of water quality impairments. The role of affected communities in securing sustainable solutions to environmental justice issues is not examined. While vulnerable populations, such as minority groups and low-income communities, are the subject of the research inquiry they are not directly interviewed. Excluding public participation via survey studies and community engagements in the search for innovative solutions to the environmental justice problem presents a limitation for this study. However, it is important to recognize that the inclusion of community participation and primary data collection will double the scope of the research and penalized the capacity for funding.

## RESULTS AND DISCUSSIONS

### Violation occurrence

The balanced panel dataset used contains 19 years and 1,710 CWSs. In this sample data, violations are not pervasive and most water systems comply each year. Compliance has improved substantially in recent years. Since 2016, 93% of systems serving 97% of the population supplied by CWS have delivered safe water. Yet, violations are present in 9.1% of water system-year observations (Table 1). From 2000 to 2018, an average of 1.0 million people each year received water from systems with health-based violations. In the years 2016–2018, 121 systems serving 0.7 million people incurred violations. Increased noncompliance might be partly because of rule changes. New federal and state regulations instituted to control chemical contaminants have added to the complexity of water quality standards. Increases in noncompliance occur immediately after the compliance dates of policy changes. For example, after the first DBP regulation required compliance for all system sizes in 2004, DBP noncompliance rises (Figure 1). Increased DBP noncompliance occurred again after 2006, when DBP monitoring became more stringent and nonconsecutive systems had to comply with DBP regulations.

**Table 1** | Variable description and summary statistics of regression sample.

| Variable | Description | Mean | SD | Min | Max |
|---|---|---|---|---|---|
| *Dependent variables* | | | | | |
| All violations | Indicator variable = 1, if water system had any violation in a given year | 0.091 | 0.288 | 0 | 1 |
| *Independent variables* | | | | | |
| Lag violations | | | | | |
| Lag, All violations | Dummy variable = 1, if water system had any violation in prior year | 0.093 | 0.290 | 0 | 1 |
| *Service Area Demographics* | | | | | |
| DAC | Dummy variable = 1, if DAC | 0.384 | 0.486 | 0 | 1 |
| SDAC | Dummy variable = 1, if SDAC | 0.109 | 0.312 | 0 | 1 |
| Latino-serving | Dummy variable = 1, if percent Hispanic population is greater than state average | 0.317 | 0.465 | 0 | 1 |
| African American-serving | Dummy variable = 1, if percent African American population is greater than state average | 0.142 | 0.349 | 0 | 1 |
| Native American system | Dummy variable = 1, if system owned or regulated by tribal government | 0.040 | 0.195 | 0 | 1 |
| *Other system characteristics* | | | | | |
| Housing density | Natural log of housing units per square mile | 4.45 | 1.90 | −1.06 | 10.9 |
| Private | Dummy variable = 1, if water system is privately owned | 0.502 | 0.500 | 0 | 1 |
| Utility size: Small | Dummy variable = 1, if water system serves <3,301 people | 0.680 | 0.466 | 0 | 1 |
| Utility size: Medium | Dummy variable = 1, if water system serves 3,301–10,000 people | 0.125 | 0.330 | 0 | 1 |
| Utility size: Large | Dummy variable = 1, if water system serves >10,000 people | 0.195 | 0.396 | 0 | 1 |
| Water source: Purchased | Dummy variable = 1, if source water is purchased water | 0.180 | 0.384 | 0 | 1 |
| Water source: Surface water | Dummy variable = 1, if source water is surface water (not purchased) | 0.175 | 0.380 | 0 | 1 |
| Water source: Ground water | Dummy variable = 1, if source water is ground water (not purchased) | 0.644 | 0.479 | 0 | 1 |
| Observations | 32,490 | | | | |
| # Counties | 58 | | | | |
| # CWS | 1,710 | | | | |

*Note:* SD, standard deviation.

Many systems also struggle with the revised arsenic MCL, which had a compliance date in 2006. As a result of the revised standard, arsenic has become the most pressing groundwater quality concern for small CWSs in California serving 10,000 people or less (SWRCB, 2015). Large water systems tend to have a good track record of compliance, whereas some small systems face more difficulty (SWRCB, 2015). For instance, in Los Angeles County, contaminated groundwater poses a challenge (Best *et al.*, 2021), particularly for smaller systems

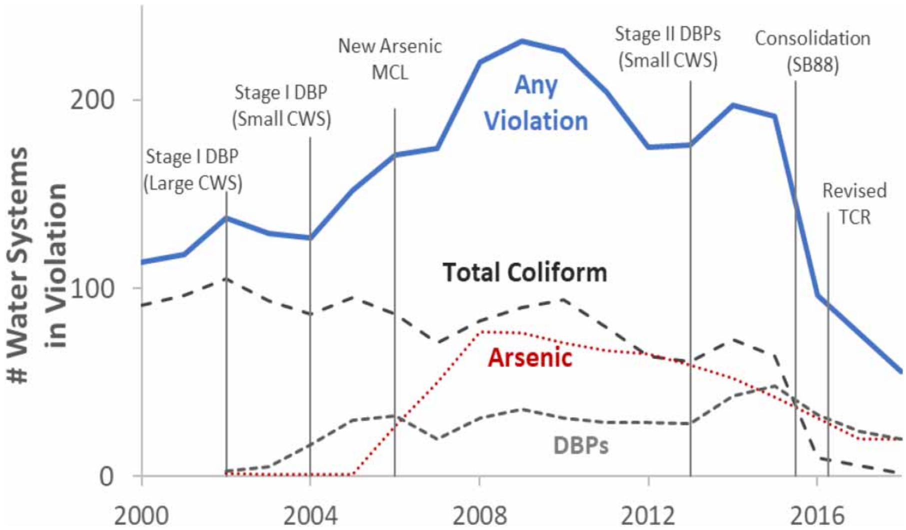



**Fig. 1** | Number of water systems in violation, 2000–2018.

(Deshazo *et al.*, 2017). Also, treatment technologies for arsenic can be costly to install and maintain, especially for small systems that lack adequate economies of scale. Despite the difficulties in meeting changing chemical standards, compliance with bacteriological standards has notably improved. The success of total coliform compliance in California might be attributable to source water protection and greater emphasis since the mid-1990s on improving surface water treatment. For example, a series of surface water rules, with compliance dates ranging between 1993 and 2005, sought to improve the removal of pathogens, especially viruses, *Giardia*, and *Cryptosporidium*. Compliance in California notably improved after 2015 (Figure 1).

Violations also vary across geographic regions due to differing source water quality and treatment capacity. Persistent violations are especially present in more rural areas than urbanized areas. Nitrate violations are largely concentrated in the SJV, and this outcome is consistent with previous studies (Harter *et al.*, 2012). Total coliform and arsenic violations are especially frequent in the Cascades region of northern California and the SJV. These outcomes also agree with past findings on the geographic distribution of arsenic concentrations (SWRCB, 2017). The most frequently occurring violations are related to total coliform (43.1%), arsenic (20.7%), and DBPs (14.4%), see Supplemental Information (Figure S1).

## Violation occurrence by demographic groups

Service area demographics vary considerably across systems. A substantial number of California utilities serve DAC (38%) and SDAC (11%) communities (Table 1). The data analyzed also include systems that are Latino-serving (32%), African American-serving (14%), and Native American (4%) Table 1. Differences in violation occurrence exist across income categories. Both DAC and SDAC systems have higher rates of total violations (12 and 17% *utility-year observations*, respectively) compared to higher-income systems (7.2% for systems not designated as DAC) (Table 2). SDAC systems face a comparatively high proportion of arsenic violations with reference to other violation types (Supplemental Information, Table S1). Differences are also apparent across race and ethnicity. Systems serving Latino communities have a more frequent occurrence of many violation types just as is the case with *Latino-serving DAC systems* (Supplemental Information, Table S1). African

American-serving systems are burdened with arsenic and DBPs. Spatial distributions of demographic categories (Supplemental Information, Figures S1 and S2) and violation occurrences (Figure 2) show relevant geographic violation hotspots and population groups disproportionately affected.

### Utility characteristics

Overall, the water systems in the sample data are highly fragmented, like systems statewide and nationwide. About 68% of systems are small, serving 3,000 people or less. Small systems are more likely to incur violations (10.2% of *utility-year observations*), compared to large systems (5.9% of *utility-year observations*). Private systems face similar violation challenges. On average, violations occur in only 1.7% of *utility-year observations* for large private utilities, compared to a larger portion at small privates (10.6%), and local governments (8.3% of *utility-year observations*) utility systems, see Table 2 below. Generally, the number of violations, regardless of the type of contaminant, are more frequent at small systems (Supplemental Information, Table S2).

Small systems are more likely to rely on groundwater sources, be privately owned, and be in rural areas. In contrast, large systems are more likely to purchase water or rely on a surface water source. Systems that rely on purchased water have fewer total violations (7.4%) compared to those relying on surface water (21.5%) or

**Table 2** | Violation occurrence, by utility-year observations.

| | % of violations | % of CWSs in total observation (32,490) |
|---|---|---|
| Utility size | | |
| Small | 10.2 | 68.0 |
| Large | 5.9 | 19.5 |
| Private* Small | 10.6 | 43.2 |
| Private *Large | 1.7 | 3.8 |
| Water source | | |
| Purchased | 3.8 | 17.9 |
| Groundwater | 10.0 | 64.4 |
| Surface water | 11.2 | 17.4 |
| Income | | |
| DAC | 12.0 | 38.4 |
| Non-DAC | 7.2 | 61.6 |
| SDAC | 17.1 | 10.9 |
| Housing density | | |
| Rural | 11.9 | 20.0 |
| Urban | 5.0 | 23.2 |
| Race | | |
| American Indian | 10.7 | 4.0 |
| African American | 11.3 | 14.2 |
| Ethnicity | | |
| Hispanic | 11.9 | 31.7 |
| Others: Local government | 8.3 | 41.7 |

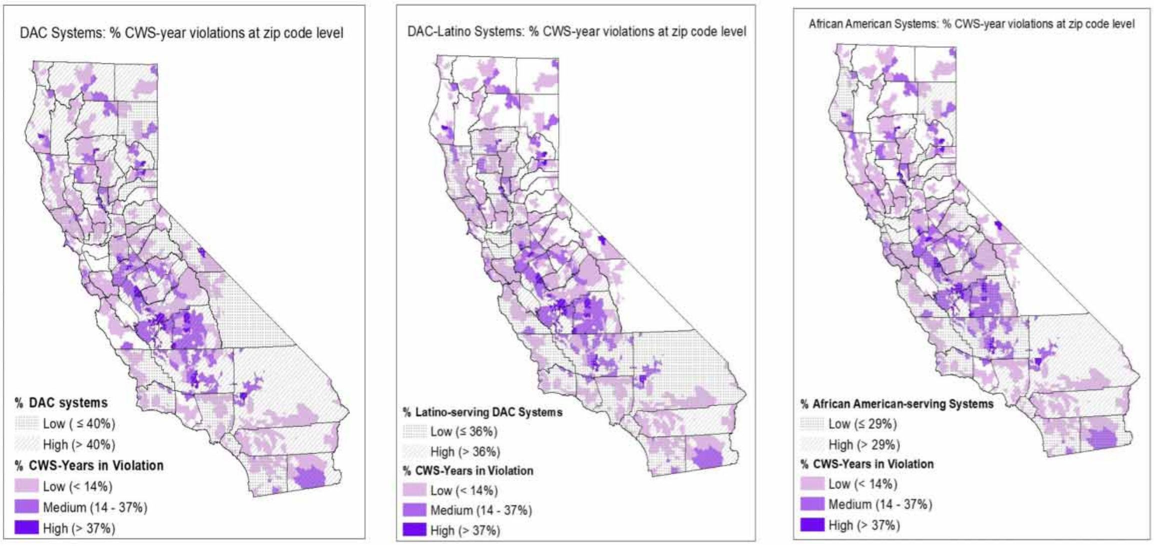



**Fig. 2** | Percent of CWS-year violations: a focus on socioeconomic systems.

groundwater (71.0%) sources (Supplemental Information, Table S2). Purchased water systems especially have fewer arsenic, nitrate, and total coliform violations (Supplemental Information, Table S2). Surface water sources have more DBP violations, which is because of the need to disinfect surface water. Groundwater sources incur more arsenic, nitrate, and total coliform violations. As expected, DBP violations under groundwater were extremely low. Of systems under private ownership, the vast majority (86.1%) are small systems. Small, private utilities include homeowner associations and mobile home parks, while large private systems are often investor-owned utilities.

## Correlation between demographics and scale

Scale factors are correlated with some service area demographics. Systems serving DACs and SDACs tend to be located in rural areas and have less private ownership. Disproportionate violations incurred at systems serving lower-income communities might be partly because of system size. DAC tends to have smaller service populations and might be less able to take advantage of economies of scale in water treatment. Similarly, Native American systems are much smaller and located in more rural areas relative to other systems. Out of all the tribal systems in California, two-thirds are very small and serve fewer than 500 people (SWRCB, 2014). In contrast, Latino- and African American-serving systems tend to be larger and in areas of greater housing density. These findings suggest that only considering scale-based factors in affordability criteria and assessments of the ability to comply will fail to capture the compliance challenges faced by communities of color.

Besides scale, other system characteristics are correlated with demographic factors. Groundwater sources are more common for Native American, Latino, DAC, and SDAC systems. Meanwhile, purchased water is more likely at African American-serving systems, but less likely for SDAC and DAC systems. Correlation also exists between demographic variables (see Supplemental Information, Table S3). The DAC and SDAC systems disproportionately serve communities of color. For example, Native American systems represent 4% of all CWSs used in the study sample, but account for 10% of SDAC systems. Likewise, Latino-serving systems make up 32% of all systems, but they make up 37% of SDACs. In addition, African American-serving systems are disproportionately DAC – these are 14% of all systems but 18% of DACs.

## Regressions

Specified regression models estimate the likelihood of violations as a function of socioeconomic and water system characteristics. Several of the socioeconomic and CWS indicators analyzed were statistically significant. This suggests that the results are not due to chance and that the significant indicators of social disparities can confidently guide policy decisions. We find that environmental justice concerns are prevalent. Low-income communities and minority groups face a greater likelihood of water quality violations. Low-income areas are more likely to have health-related violations. Systems that served DAC are 1.7% (Table 3, Model 1) more likely to incur any violation; this increases to 3.4% (Table 3, Model 2) and 2.6% (Table 3, Model 3) for SDACs.

In terms of specific contaminants, the likelihood of Total Coliform violations is positively associated with DAC, SDAC, young children (aged five and below), and Latino-serving systems (Supplemental Information, Table S6). The observed 1% increase in TCR violation likelihood under DAC increases further (1.3%) for SDAC (Supplemental Information, Table S6, Model 4). Latino-serving and African American systems face an increased likelihood of approximately 1%. This likelihood is considerable given that total coliform violations are present in only 4.1% of water system-year observations (total number of observations – 32,490). Total coliform might pose a risk to tribal water systems because of their heavy reliance on groundwater sources and being more likely to serve small populations and SDACs. Tribal water systems are 2% more likely to violate TCR (Supplemental Information, Table S6; Model 2).

**Table 3** | Regression results – ME, total violations.

| | Model 1 | | | Model 2 | | | Model 3 | | |
|---|---|---|---|---|---|---|---|---|---|
| | ME | | Std. Err. | ME | | Std. Err. | ME | | Std. Err. |
| Lag violation | 0.3894 | *** | 0.0091 | 0.3869 | *** | 0.0091 | 0.3764 | *** | 0.0091 |
| Private | −0.0016 | | 0.0031 | −0.0020 | | 0.0031 | −0.0017 | | 0.0031 |
| Medium | −0.0010 | | 0.0047 | −0.0007 | | 0.0047 | −0.0042 | | 0.0046 |
| Large | −0.0195 | *** | 0.0052 | −0.0186 | *** | 0.0053 | −0.0227 | *** | 0.0052 |
| Water source = purchased | −0.0280 | *** | 0.0041 | −0.0297 | *** | 0.0040 | −0.0253 | *** | 0.0042 |
| Water source = surface water | 0.0063 | * | 0.0038 | 0.0054 | | 0.0038 | 0.0123 | *** | 0.0040 |
| DAC | 0.0177 | *** | 0.0030 | | | | | | |
| SDAC | | | | 0.0344 | *** | 0.0048 | 0.0269 | *** | 0.0046 |
| Young children | | | | | | | 0.0289 | *** | 0.0031 |
| ln(housing density) | −0.0048 | *** | 0.0009 | −0.0046 | *** | 0.0009 | −0.0059 | *** | 0.0009 |
| Year fixed effects | Yes | | | Yes | | | Yes | | |
| Log likelihood | −7,783 | | | −7,772 | | | −7,729 | | |
| LR $\chi2$ | 4,086 | | | 4,110 | | | 4,131 | | |
| Prob > $\chi2$ | 0.000 | | | 0.000 | | | 0.000 | | |
| McFadden's $R^2$ | 0.214 | | | 0.215 | | | 0.220 | | |
| $N$ | 32,490 | | | 32,490 | | | 32,490 | | |

*Note:* ME, marginal effects; Std. Err., standard error.
Significance (Sig): *** $p < 0.01$, * $p < 0.1$.

Arsenic violations are estimated to be more likely at DAC, SDAC, and African American-serving systems (Supplemental Information, Table S8). Young children are also more susceptible to arsenic contaminant violations. Water systems facing arsenic violations are more likely to affect young children than older adults. There was no significant association between arsenic violations and tribal water systems or Hispanic-serving water systems. Some water systems in California struggling to comply with the revised arsenic MCL are considering consolidation (SWRCB, 2015). Our study finds that about 2% of CWS violated the revised arsenic MCL. Nitrate violations have a greater likelihood of occurrence at DAC, SDAC, and Latino-serving systems (0.54 percentage points). In our sample, 0.9% of system-year observations have nitrate violations. While the proportion of water systems (CWS) facing nitrate violation is small compared to TCR, arsenic, and DBP violations, its effect on DAC, Latino populations and children under the age of five is significant (Supplemental Information, Table S10). Higher likelihood of DBP violations is associated with communities of color and vulnerable populations, but not with income. Latino-serving and African American-serving systems face an increased probability of violations of approximately 1 and 0.5% percentage points, respectively (Supplemental Information, Table S10). A higher likelihood of DBP violations might be explained by Latino-serving systems relying on surface water as a source, especially among systems not designated as DAC. A 1% increase in DBP violations of water systems is more likely to affect young children under the age of five.

Additionally, significant effects of CWS violations on other water system characteristics were observed. Previous violations characterized as lag violations were positively associated with a higher likelihood to contaminant violation currently incurred. A 1% increase in lag violations increases the likelihood of TCR, arsenic, nitrate, and DBP violations by 13.0, 69.9, 53.3, and 30.9%, respectively (see, Model 1 of Supplemental Information, Tables S6, S8, S10, S12). The observed ME have huge implications for failure to address previous water contaminant violations. Water system characteristics such as utility size, source of water and ownership have impacts on CWSs although the effects are specific to water quality contaminant type. For instance, privately owned utility systems are more likely to violate the maximum allowable nitrate contaminant level. Also, purchased water and surface water sources decrease the likelihood of TCR, arsenic, and nitrate violations but increase the probability of violations in the case of DBPs. However, large CWS are less likely to influence DBPs violations. Larger systems are associated with a lower likelihood of DBP noncompliance. The research findings reveal insights for future research. The identified study limitations could be addressed by targeting location specific research that investigates further the participation and engagement of stakeholders in the fight against environmental justice of impaired drinking water. Also, additional research could examine the sustainable co-benefits of the policy guidance that this study recommends. More importantly, economic valuation of the policy outcomes could be a crucial motivation factor for policy adoption.

## Highlight of Figure 1

Figure 1 shows the inherent struggle of water utilities with the management of contaminant violations following rule adjustments. Arsenic and DBPs offer clear case scenarios. The revised arsenic rule in 2006 saw increased violations. Likewise, changes to the DBP rules in 2004 and 2013 show similar spikes in violations.

## Highlight of Figure 2

Figure 2 shows areas in California where minority groups and low-income communities are disproportionally burdened by drinking water quality impairments. The SJV shows persistence (as found in prior studies) and a strong case for environmental justice of water quality violations. Additional geographic areas in southern California (for instance, the Imperial and San Diego Counties) are beginning to show similar environmental justice concerns.

Figure 2 does not show violation by type but rather it seeks to communicate geographic hotspots of total CWS-year violations.

## CONCLUSION

Results from the study provide evidence of disparities in drinking water quality across California. Environmental justice concerns are evident for minority and vulnerable populations. The case of water quality violations is worsened by populations living in DAC. Hispanics, Native Americans, and African American populations are disproportionately burdened by water quality contaminant violations. Latinos are disproportionately affected by TCR, nitrate, and DBP violations while Native Americans face disproportionate exposure to TCR violations and African American populations were associated with increased likelihood of arsenic, TCR, and DBP violations. Addressing current disparities is crucial for water quality improvement and the minimization of the future impact of contaminant violations disproportionately facing minority groups.

Some CWS characteristics are key to managing water contaminant violations. The results revealed the propensity of large utility systems and purchased water sources to reduce water quality violations (Table 3). The technical, managerial, and financial (TMF) capacity of the State Water Board to support large water systems may focus on integrating purchased water or surface water as primary sources for CWS since these water system characteristics might lead to significant reductions in the probability of observing arsenic, nitrate and total coliform violations. Also, the State Water Board may consider the possibility of merging small water systems into large utilities to prevent the proliferation of small CWS and the likelihood of increasing contaminant violations. The merging of smaller utility systems could support the better distribution of limited water resources statewide while limiting systemic environmental injustice issues specific to water quality violations.

Overall, the results provide relevant evidence that supports critical concerns over minority groups bearing a disproportionate burden of water quality impairment. In-depth understanding of the most affected regions or population groups is key to water resource management and planning decisions. While federal and state assistance might be available to struggling communities, targeting assistance can be challenging because of the limited information on populations disproportionately burdened by water quality impairment. Our findings address such a knowledge gap for the optimal distribution of state water resources to support water quality improvement, especially within underserved communities. The findings discussed in this paper can advance the understanding of vulnerable communities and the call for environmental justice associated with drinking water quality. Based on these findings, it is recommended that the California Water Board engage utility water managers in discussions regarding the potential merging of failing small water systems for better management and allocation of funding. The board can also create an incentive for water managers' commitment toward addressing prior violations. If possible, the water board may fund additional research to investigate the willingness of affected communities to engage in proactive and innovative solutions to the problem of water quality impairments within their communities.

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## DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

## CONFLICT OF INTEREST

The authors declare there is no conflict.

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