Title

Social Disparities and Health Risk Assessment of Selected Inorganic Constituents in Domestic Well Water within the UC Davis Comprehensive Cancer Center Catchment Area

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Social Disparities and Health Risk Assessment of Selected Inorganic Constituents in Domestic Well Water within the UC Davis Comprehensive Cancer Center Catchment Area

By

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THESIS

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Abstract

Groundwater provides 40–60% of California's water supply. However, domestic well water quality is not regulated in California due to its decentralized nature and high cost of testing. Many well water users rely on regional groundwater monitoring data (e.g. Groundwater Ambient Monitoring and Assessment) for information about their water quality but there remains a need for an integrated approach that combines place-based quantitative analysis with cancer risk assessment and community engagement. Our pilot study aims to build relationships and science literacy with private well water users through compensated community sampling of California well water and provision of quantitative reports including 22 inorganic constituents (e.g. lead, arsenic, nitrate) with primary and secondary MCLs. Additionally, the pilot study seeks to investigate the impacts of seasonality, land use, and climate change phenomena (e.g. wildfire, drought, floods) on well water quality. Participants (n=113) were recruited in collaboration with our community partner, the Environmental Justice Coalition for Water. Chemical analyses were performed at UC Davis and used to generate water quality reports and to assess potential public health risks and resources for remediation (see Figure A6 in Appendix). Of the 113 well samples tested, 14 (12.4%) had at least one constituent exceedance of Primary Maximum Contaminant Levels (MCLs), 74 (64.5%) had at least one constituent exceedance of Secondary MCLs, and all had at least one constituent exceedance of Public Health Goals (PHGs) and Notification Levels (NLs) (e.g. Lead (57/57), Uranium (28/57), Arsenic (12/57), Cadmium (11/57)). This study will help study participants assess the health risks associated with consumption of their well water and provides the infrastructure to scale up to a larger community-based groundwater quality monitoring program.

Acknowledgements

This research was conducted through the collaboration between the Environmental Justice Coalition for Water (EJCW) in Stockton, CA, and several groups at the University of California, Davis in Davis, CA, including the UC Davis Comprehensive Cancer Center, the UC Davis Department of Public Health Sciences, the UC Davis Environmental Health Sciences Center, and the UC Davis Department of Civil and Environmental Engineering. I would like to thank Dr. Kyounglim Kang, Kelly Lu, Elizabeth Whelan, Madeline Keck, and Amber Yehualashet Dekker for providing laboratory and analytical support. Additionally, I extend a special thank you to Espe Vielma, Maritza Juache, and the Promotoras of EJCW, whose community expertise and relationships were instrumental to building trust with underrepresented and underserved communities to provide a more accurate scientific reflection of the landscape. Last but certainly not least, thank you to Jackie, Beth Rose, Shehnaz, and Tom, for your generous support and guidance in the multiple adaptations of this thesis. This work was supported in part by the UC Davis Comprehensive Cancer Center (P30CA093373).

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Introduction

Groundwater is an essential global resource as the greatest container of freshwater second to glaciers. In California, groundwater provides an average of 40% of the State's water supply, and up to 60% of the State's water supply in dry years. Up to 2 million Californians rely exclusively on groundwater (e.g. domestic well water users), making these communities especially susceptible to the variability of water quality resulting from geologic context, land use, seasonality, and perturbations associated with climate change [8]. As drought, flooding, wildfire, and other climate change phenomena increasingly impact the natural and managed landscape, California communities are increasingly expected to become water scarce and rely on groundwater as a drinking water source [22].

Inorganic constituents of concern can be naturally occurring in the sediments that comprise a groundwater basin. As groundwater passes through the rocks and sediments, metals (e.g. mercury, lead) and radionuclides (e.g. uranium, radium) can be dissolved into the groundwater, at times at concentrations above health-based regulatory standards. Residential, urban, and industrial waste discharge can shape groundwater quality by introducing contaminants and altering the pH, dissolved oxygen, redox potential, and other geochemical properties that shape chemical speciation. Additionally, pesticides, insecticides, fertilizers, manure, and other agricultural field applications can migrate from fields and lawns to the water table [21]. Seasonal changes in the water table height through natural (e.g. wet/dry seasons) and anthropogenic (e.g. groundwater overdraft, managed aquifer recharge) events can alter the concentration of constituents by changing the groundwater's redox potential, accumulation, and rate of dissolution of constituents. In addition to increasing reliance on groundwater due to constraints on surface water quantity and quality, climate change events are projected to increase the number of out-of-compliance water systems.

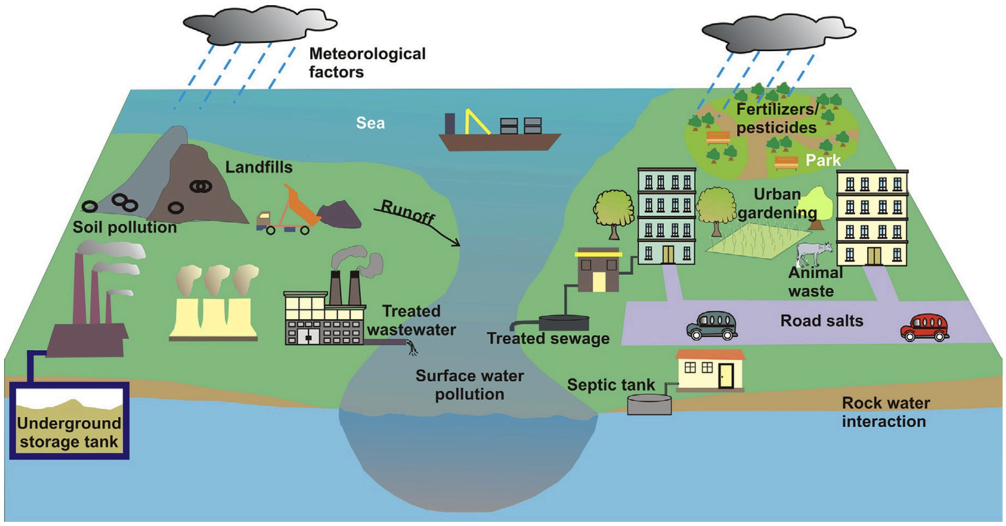


Figure 1: Impacts of Urbanization on Groundwater Quality. Graphic source: [21].

In California, domestic wells are not regulated for their water quality under the state Clean Water Act or the Federal Safe Drinking Water Act due to their decentralized nature and high cost of testing. This puts a disproportionate burden on domestic well water users to test their water quality for constituents of concern and understand the sources of risk to their drinking water. Many well users rely on regional groundwater monitoring data (e.g. Groundwater Ambient Monitoring and Assessment) for information about their water quality, but there remains a need for an integrated approach combining place-based quantitative analysis with health risk assessment and community engagement. Research increasingly calls for novel monitoring approaches, including citizen science projects, to address the water quality data shortage and to improve community education on groundwater issues. Despite a rise in citizen science water quality monitoring, many projects focus on surface water data collection, and there remains a shortage of groundwater data [13; 19].

Public drinking water systems are monitored and regulated by the state and federal government through the Clean Water Act (1972) and the Safe Drinking Water Act (1974), respectively. Both pieces of legislation include regulatory limits for over 90 constituents, taking into account the known human health risks of acute and chronic exposure as well as technological and economic limitations of remediation. In public drinking water systems, health-based enforceable regulatory standards are known as primary Maximum Contaminant Level (MCLs), Response Level (RLs), or Action Levels (ALs). Secondary MCLs are aesthetic-based standards that affect water color, odor, and taste, (e.g. iron, sulfate, chloride). Concentrations below Public Health Goals (PHGs) and Notification Levels (NLs) pose no known health risks. While the state regulates these standards in public drinking water systems, the quality and safety of domestic wells is not regulated, leaving well owners responsible for assessing the potential health risks of drinking water from their tap [8]. According to the California Environmental Protection Agency (CalEPA), "The State of California does not regulate water quality in private domestic wells…Comparing your well's test results to public drinking water standards can be helpful." This study seeks to compare domestic water quality to public drinking water standards to build confidence for well water users in making decisions about their water use.

While domestic well water does not receive the same protections as public drinking water systems, all people in California are protected by Water Code Section 106.3, formerly known as Assembly Bill 685 (2012), which legislatively recognizes the human right to clean, affordable, and accessible water. This legislation received 130 million dollars of funding from Senate Bill

200 (2020) to support implementation of remediation, consolidation, and bottled water distribution efforts in communities impacted by out-of-compliance water systems. The bills acknowledge the disproportionate impact of unsafe water in underrepresented and underserved rural and urban communities in California [20].

While there is water justice analysis of small/community water systems, there is a paucity of analysis on domestic well water quality. A 2021 Office of Environmental Health Hazards Assessment (OEHHA) study of small community water systems (<15 connections) in California found that nearly a third of all community water systems had MCL exceedances for at least one contaminant. Disadvantaged/severely disadvantaged community water systems had worse water quality than non-disadvantaged ones, and small/very small systems faced greater affordability challenges [2]. A 2023 study found that historically disenfranchised communities (e.g. low-income, minority groups) faced greater likelihood of water quality violations, with children aged five and under being more likely to be exposed to constituents with health-based regulatory standards [1].

This pilot study seeks to address the gaps in domestic well water quality data through citizen science monitoring. The inorganic constituents were measured and compared to public drinking water standards to contribute a better understanding of well water safety. The statistical relationships between water quality and land use, socioeconomic status, recruitment methods, and climate change events were determined to better understand how these variables contribute to non-carcinogenic health risks. Lastly, the possibility of scaling up the pilot study to address the groundwater quality data gap was assessed with recommendations for future study iterations.

Methods

Site Description and Sample Collection

Domestic well samples (n = 113) were collected by study participants and mailed to the Peña Laboratory at UC Davis. Participants were recruited from the UC Davis Comprehensive Cancer Center Catchment area, composed of 19 inland northern California counties. Participants were mailed or distributed kits at recruitment events, which contained sampling instructions (see Figure A5 in Appendix). The eligibility requirements were that users had access to retrieve water samples from a domestic well in California, and that they had enough water to allow the water to run continuously for at least one minute prior to sampling. A short survey including questions about localized phenomena (e.g. pesticide/fertilizer application, nearby wildfire/flooding) and demographic data (e.g. Language preference) was the primary source of parameter metadata, in addition to CalEnviroscreen 4.0 and the 2020 Census (e.g. Low Income CA Percentile by Census Tract, People of Color CA Percentile by Census Tract). Percentile values were used instead of percentages in order to provide more stratified and normalized results that could better indicate how common or exceptional a case was within the state.

Trace Metal Analysis

Samples were collected in 250 mL Diamond® RealSeal™ Rectangular HDPE bottles and stored in a cold room at 4ºC upon reception at the Peña laboratory. The samples were filtered through a 0.22 micron filter to remove TDS and protect the instrument. In order to prepare 10 mL of a diluted sample, 1 mL of the original sample was added to 8 mL of deionized water and 1 mL of 10% nitric acid, acidifying the diluted sample to a 1% nitric acid solution. The samples were diluted to reduce the matrix effects associated with high ionic strength groundwater while remaining above the instrument detection limit.

The diluted samples were then loaded onto the ICP-MS instrument. The selected trace metals were analyzed, each calibrated with a NIST standard, 10 standards of varying concentrations (ranging 0.01-250 ppb), as well as quality control (QC) measurements of 5 and 10 ppb and blanks spaced after running every ten samples. Standard drift and dilutions were adjusted to produce the final concentration of each constituent, which was then compared to the limit of quantification for the instrument.

Statistical Analysis

Samples were grouped by the parameter indicators of socioeconomic status, climate change events, and land use. Parameters representing socioeconomic status included “Language Preference”, “Low Income Percentile” and “People of Color Percentile”, which was the preferred language of communication indicated in the survey, census tract level values for state percentiles of low income communities, and census tract level values for state percentiles of communities of color, respectively. Parameters representing land use included “Fertilizers” and “Pesticides”, or the application of fertilizers or pesticides within a year of sample collection and 100 feet from the sampled well location. Parameters representing climate change events included “Wildfire” and “Flooding”, or the occurrence of a flooding or wildfire event within five years of sample collection and a mile from the sampled well location. “Recruitment Method” characterized samples from participants recruited through door-to-door and community event recruitment through EJCW based in Stockton, CA, and the UC Davis Health Article, which reached participants across northern California, predominantly in the foothills of the Sierra Nevada mountains.

Due to the large number of inorganic constituents (n = 23) and parameters (n = 8), a subset of four constituents were chosen for more extensive analysis. The four constituents that would be selected for further exploration were those that had health-based regulatory standards and displayed the largest quantity of statistically significant differences with respect to the parameters for socioeconomic status, climate change, and land use.

The selected constituents satisfying this criteria were assessed by their descriptive statistics and compared to the relevant regulatory drinking water standards. The normality of each dataset was determined using a quantile-quantile plot, equal variance was demonstrated using an f-test, and independence was determined using the chi-squared test of independence. If the data did not satisfy these requirements, non-parametric analyses would need to be performed instead of more powerful parametric ones. The Mann-Whitney U-Test, the non-parametric equivalent to the two-tailed T-test, was performed to compare two independent groups with a continuous/ordinal outcome to determine if they display statistically significant differences with at least 95% confidence. The Spearman Correlation Analysis, the non-parametric equivalent to the Pearson Correlation Analysis, was used to explore if there is a statistically significant correlation between two continuous/ordinal variables with at least 95% confidence. Lastly, the Kruskal-Wallis Test, the non-parametric equivalent to ANOVA, would be employed to compare three or more groups on a continuous or ordinal outcome. In the case that there was a statistically significant difference between at least a pair of the groups, a Dunn-Bonferroni Test was used to determine which pair(s) of groups exhibited statistical differences.

The p-value was the output of all tests, and was used as a measure of statistical significance. Values lower than 0.05 indicated either a statistically significant correlation (Spearman Correlation) or differences (Mann-Whitney U-Test, Kruskal-Wallis Test) with 95% confidence between groups. The r-value demonstrated the strength of the effect/correlation of a given parameter on the concentration of the inorganic constituent.

Non-Carcinogenic Health Risk Assessment

Using a method from Sakizadeh (2015), the non-carcinogenic health risk was estimated using the concentrations of the selected trace metals. The hazard quotient was evaluated using the following equations:

$$D_i = \frac{C_i * IR * EF * ED}{B_W * AT} \quad (1)$$

$$HQ = \frac{D_i}{RfD} \quad (2)$$

Equation (1) calculates D_i ($\mu g kg^{-1} day^{-1}$), the daily dose of heavy metals that well water users may be exposed to. C_i (µg/L, or ppb) represents the concentration of a given heavy metal in the water. IR (L/day) was the ingestion rate of the tested water, or the volume of water ingested each day. EF (days/year) represents the exposure frequency to the tested water, or the number of days in a year that water is ingested. ED (years) represents the total duration of exposure to the tested water, or the number of years that water is ingested in a lifetime. B_w (kg) represents body weight, assumed to be constant for adults regardless of gender. AT (days) represents the average time consumers are exposed to the tested water in a lifetime. Equation (2) calculates HQ (unitless), the hazard quotient of heavy metals, which demonstrates high risk of non-carcinogenic health impacts when exceeding a value of 1. RfD ($\mu g kg^{-1} day^{-1}$) is the reference dose for each given metal, standardized by the United States by the Environmental Protection Agency (USEPA). Non-detectable (ND) values, or values below the limit of quantification (LOQ) of the instrument, were set equal to zero for calculations.

Constant	Units	Value	Reference
IR	L/day	2.2	Sakizadeh (2016)
EF	days/year	365	Sakizadeh (2016)
ED	years	70	Sakizadeh (2016)
B_W	kg	60	Sakizadeh (2016)
AT	days	2550	Sakizadeh (2016)
$RfD_{Arsenic}$	$\mu g kg^{-1} day^{-1}$	0.3	USEPA IRIS (1991)
$RfD_{Cadmium}$	$\mu g kg^{-1} day^{-1}$	0.5	USEPA IRIS (1989)
$RfD_{Chromium}$	$\mu g kg^{-1} day^{-1}$	3	USEPA IRIS (1998)
RfD_{Copper}	$\mu g kg^{-1} day^{-1}$	40	USEPA IRIS (1988)
$RfD_{Manganese}$	$\mu g kg^{-1} day^{-1}$	140	USEPA IRIS (1995)
$RfD_{Nitrate}$	$mg kg^{-1} day^{-1}$	1.6	USEPA IRIS (1987)
$RfD_{Nitrite}$	$mg kg^{-1} day^{-1}$	0.1	USEPA IRIS (1991)
RfD_{Lead}	$\mu g kg^{-1} day^{-1}$	7E-4	USEPA IRIS (2004)

$RfD_{Selenium}$	$\mu g kg^{-1} day^{-1}$	0.5	USEPA IRIS (1991)
$RfD_{Uranium}$	$\mu g kg^{-1} day^{-1}$	3	USEPA IRIS (1989)
$RfD_{Vanadium}$	$\mu g kg^{-1} day^{-1}$	9	USEPA IRIS (2012)

Table 1: Constants used in equations (1) and (2) to determine daily dose of heavy metals (D_I) and hazard quotient (HQ).

Results

Spatial Distribution

The recruitment process impacted the geographic clustering of the data; the Environmental Justice Coalition for Water (EJCW), based in Stockton, CA, contributed the majority of samples (n=61) through door-to-door recruitment in the larger Stockton area and Eastern San Joaquin Groundwater Basin region (n=60). The Eastern San Joaquin Groundwater Basin deposits are predominantly composed of fine sand and clay, with a groundwater storage capacity of 42.4 million acre feet (MAF) and concerns of saltwater intrusion and nitrate contamination. The second recruitment method used was a UC Davis Health article, which accounted for nearly half (n=52) of the samples, many of which were from the Sierra Nevada Foothills (n=29). The Sierra Nevada Foothills contains groundwater in the fractured-bedrock composed of granitic and metavolcanic rock and sediments which have varied effects on water quality.

Sample Collection Month	Count
April '23	1 (0.88%)
May '23	7 (6.19%)
June '23	14 (12.4%)

July '23	45 (39.8%)
August '23	41 (36.3%)
September '23	5 (4.42%)

Table 2: Distribution of Sample Collection Month. Nearly two-thirds of all samples were collected in July and August 2023.

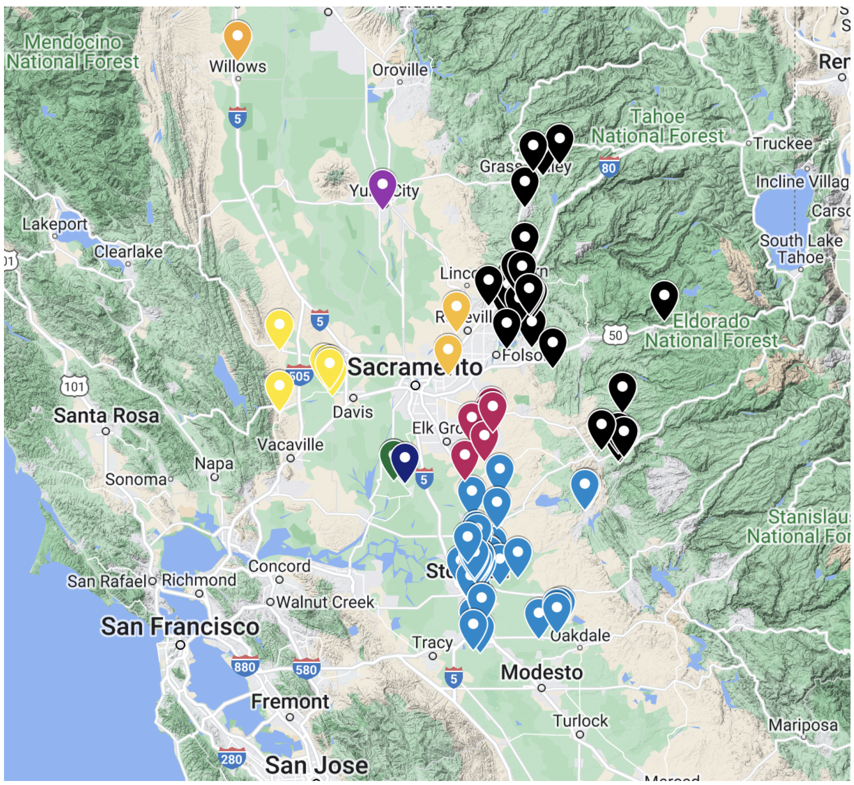


Figure 2: Map of Sample Collection in the Comprehensive Cancer Center Catchment Area, Color-Coded by groundwater basin. The Environmental Justice Coalition for Water (EJCW) recruited participants (n=61) in the Eastern San Joaquin Groundwater Basin (blue); the UC Davis Health article recruited participants from the larger catchment area, the majority of which were from the foothills of the Sierra Nevada mountains (n=29). Due to the close proximity of some of the domestic wells, some of the well locations are not visible.

Descriptive Statistics

The distributions of all of the inorganic constituents with health-based standards are right-skewed, indicating the need for non-parametric hypothesis testing and correlation analysis. The skewed distributions of the 11 constituents with health-based standards are shown below.

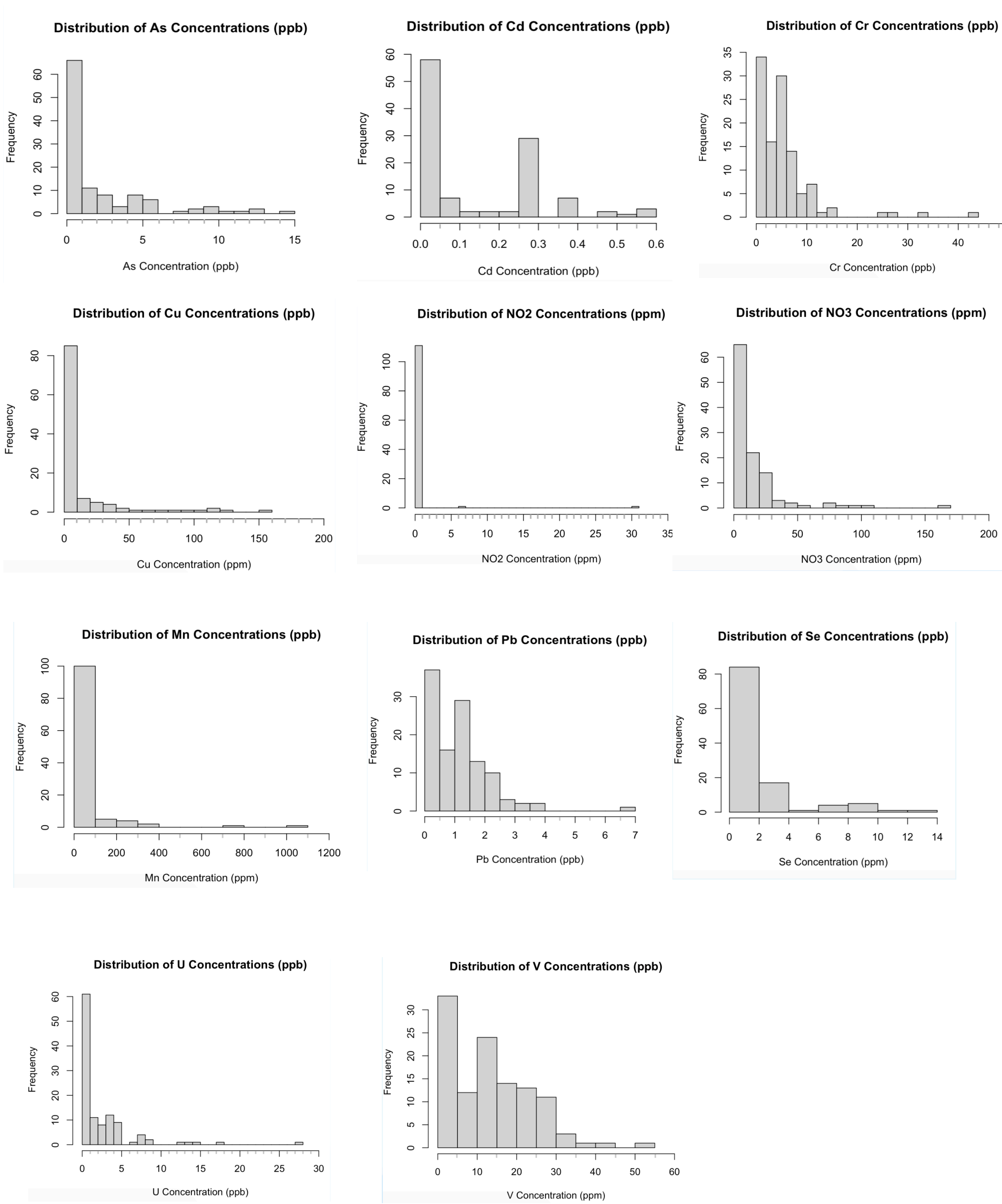


Figure 3: Histograms of inorganic constituents with health-based regulatory standards. The histograms of inorganic constituents with aesthetics-based regulatory standards (e.g. secondary MCLs) and with no regulatory standards can be found in the appendix.

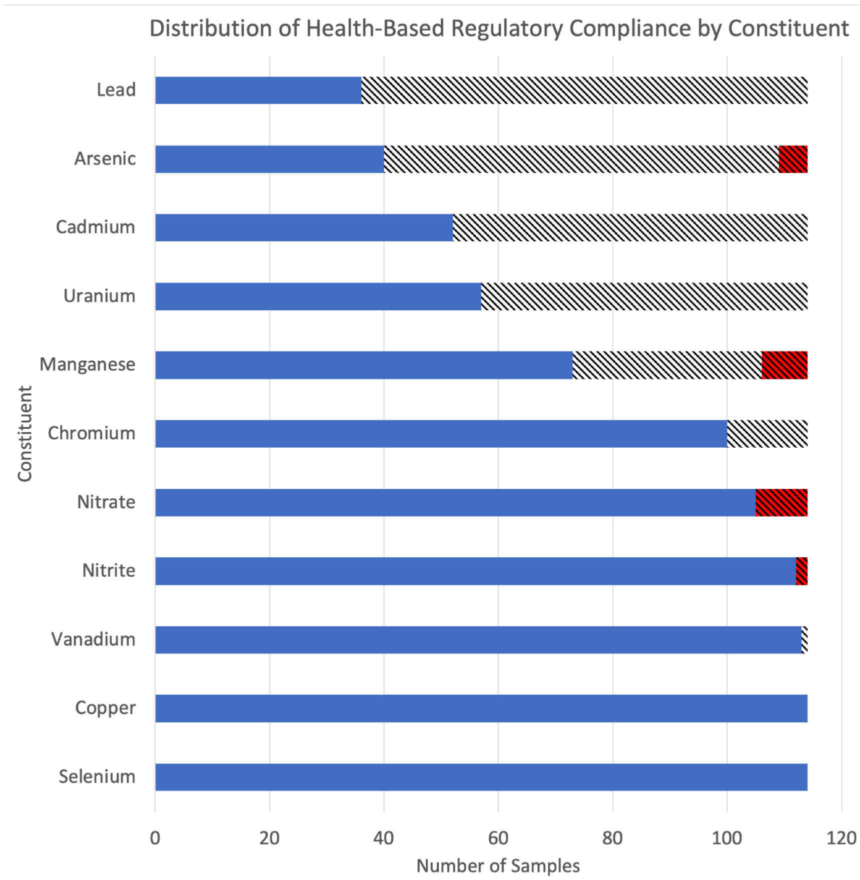


Figure 4: Distribution of Health-Based Regulatory Compliance by Constituent. The constituents with highest number of MCL/RL exceedances included nitrate (n = 9/113, 8.0%), manganese (n =8/113, 7.1%), arsenic (n = 5/113, 4.4%), and nitrite (n = 1/113, 0.9%). The constituents with highest number of PHG/NL exceedances included lead (n = 75/113, 66.4%), arsenic (n = 68/113, 60.2%), cadmium (n = 61/113, 54.0%), and uranium (n = 56/113, 49.6%).

Table 3: Statistically significant correlations/effects between inorganic constituents with health-based regulatory standards and parameters. All cells with a green/blue color and an r-value indicate a p-value less than or equal to 0.05, and the strength of the effect/correlation. "N" indicates a p-value greater than 0.05, signaling no significant correlation or difference.

Parameter Type	Parameter	As*	Cd*	Cr	Cu	NO_2	NO_3	Mn	Pb	Se	U*	V*
Socioeconomic	Language Preference[1]	0.18	0.25	N	N	N	N	N	N	N	0.26	0.27
	Low Income Percentile[2]	0.26	0.34	N	N	N	N	-0.22	N	N	0.30	0.22
	People of Color Percentile[2]	N	N	0.20	N	N	N	N	-0.20	N	0.42	0.43
Climate Change	Flooding[1]	0.31	N	N	N	N	N	N	N	N	N	0.39
	Wildfire[1]	N	N	N	N	N	-0.28	N	N	N	N	N
Land Use	Fertilizers[1]	N	N	N	N	N	N	N	N	N	N	N
	Pesticides[1]	N	N	N	N	N	N	N	N	N	N	N

Legend	N				
Strength of Effect/Correlation	No stat. sig. difference ($p \geq 0.05$)	$p < 0.05$, Very Low ($\|r\| < 0.1$)	$p < 0.05$, Low ($0.1 \leq \|r\| < 0.3$)	$p < 0.05$, Medium ($0.3 \leq \|r\| < 0.5$)	$p < 0.05$, High ($0.5 \leq \|r\|$)

*The four inorganic constituents with health-based regulatory standards and with the highest counts of statistically significant differences were selected for further analysis, which include As, Cd, U, and V.
[1] Mann-Whitney U-Test used to determine p-value.
[2] Spearman Correlation used to determine p-value.

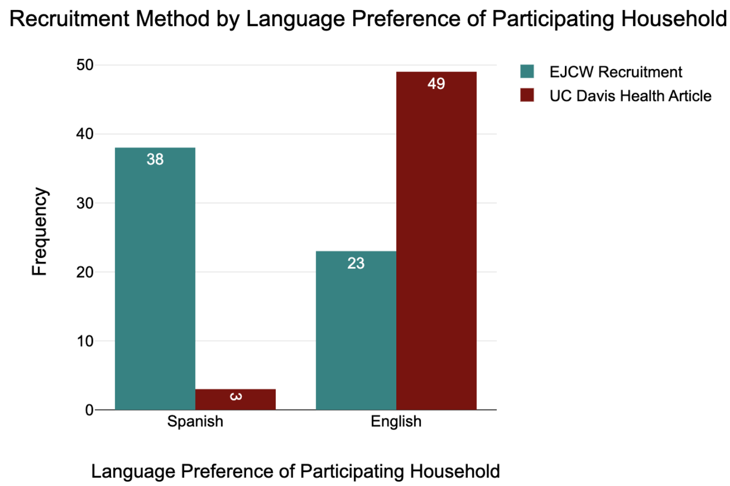
The arsenic, cadmium, uranium, and vanadium concentrations had ranges of ND-14.97 ppb, ND-0.60 ppb, ND-27.44 ppb, and ND-52.12 ppb, respectively. The Interquartile Range (IQR) for arsenic, cadmium, uranium, and vanadium across samples was ND-2.80 ppb, ND-0.27

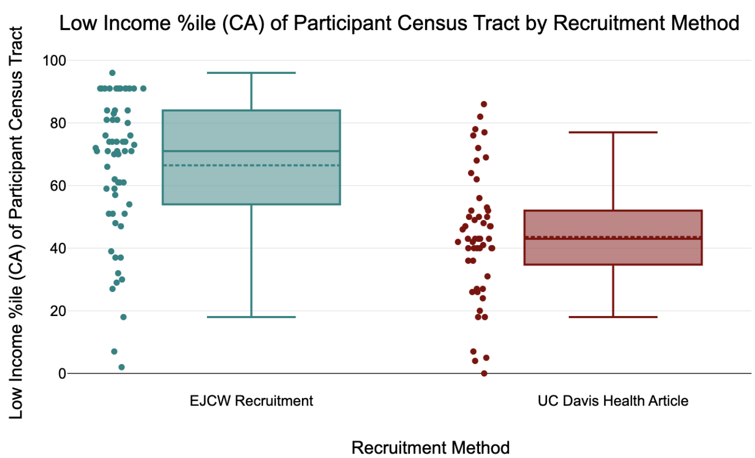
ppb, 0.03-3.13 ppb, and 4.48-20.72 ppb, respectively. Values that are below the limit of quantification (LOQ) are written as ND (non-detectable). The LOQ and health-based regulatory standards of each constituent is shown below. The only constituent with exceedances of enforceable drinking water standards (e.g. MCL/RL) was Arsenic, which had 5 (4.4%) samples above the MCL of 10 ppb. The constituents with exceedances of non-enforceable drinking water standards included arsenic (n = 68, 60.2%), cadmium, uranium, and vanadium.

Table 4: Sample Distribution and Regulatory Compliance of Selected Inorganic Constituents.

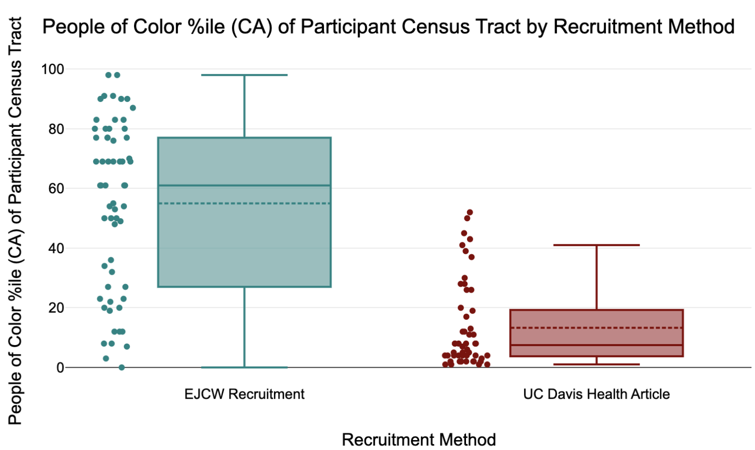
	As (ppb)	Cd (ppb)	U (ppb)	V (ppb)	Source
Min	ND	ND	ND	ND	-
Q1	ND	ND	0.03	4.48	-
Median	0.15	0.04	0.64	11.50	-
Q3	2.80	0.27	3.13	20.70	-
Max	15.00	0.60	27.40	52.10	-
LOQ	0.02	0.00	0.00	0.00	-
State MCL/RL	10.00	5.00	30.00	-	OEHHA
State PHG/NL	0.00	0.04	0.65	15.00	OEHHA
# Sample Concentrations above MCL/RL	5 (4.4%)	0 (0.0%)	0 (0.0%)	0 (0.0%)	-
# Sample Concentrations between PHG/NL and MCL/RL	63 (55.8%)	61 (54.0%)	56 (49.6%)	44 (38.9%)	-
# Sample Concentrations below PHG/NL	45 (39.8%)	52 (46.0%)	57 (50.4%)	69 (61.1%)	-

EJCW recruitment accounted for 92.7% (n = 38) of all participants with a Spanish language preference and 31.9% (n = 23) of participants with an English communication preference, whereas 7.3% (n = 3) and 68.1% (n =49) came from the UC Davis Health Article, as shown in Figure 5 below. A Mann-Whitney U-Test demonstrated a statistically significant difference between the EJCW Recruitment and UC Davis Health Article with respect to the dependent variables Low-Income Percentile and People of Color Percentile (U = 339, p = <.001, r = 0.49, and U = 685.5, p = <.001, r = 0.68, respectively), demonstrating EJCW Recruitment had higher values of both low income percentiles and people of color percentiles, visible in Figures 6 and 7.





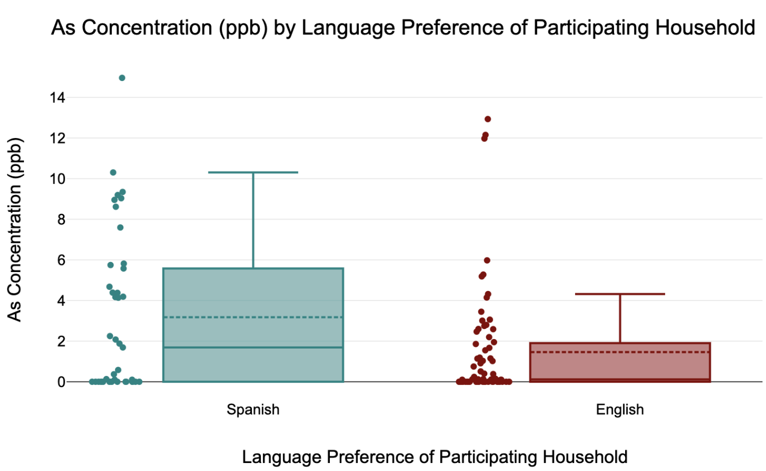
p-value	r-value
<0.001	0.68



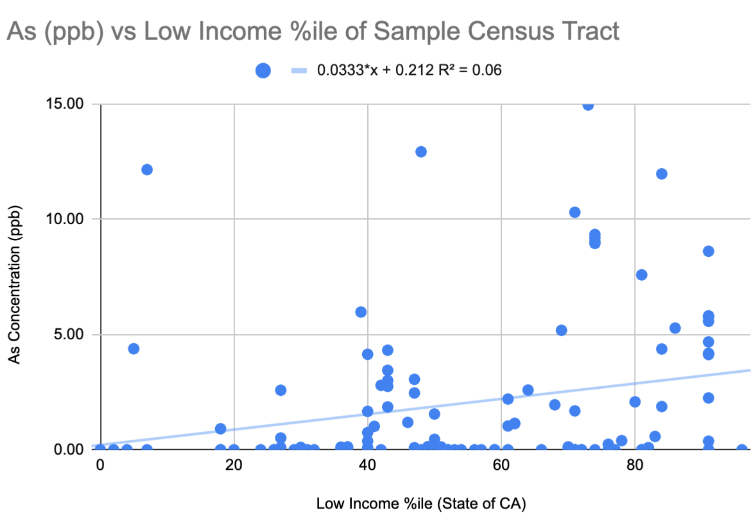
p-value	r-value
<0.001	0.49

Figure 5: Bar graph of Recruitment Method vs Language Preference of study participants and box plots of Recruitment Method vs Low Income Percentile of study participants, and Recruitment Method vs People of Color Percentile of study participants. The middle solid lines in the box plots represent the median, and the dotted lines represent the mean.

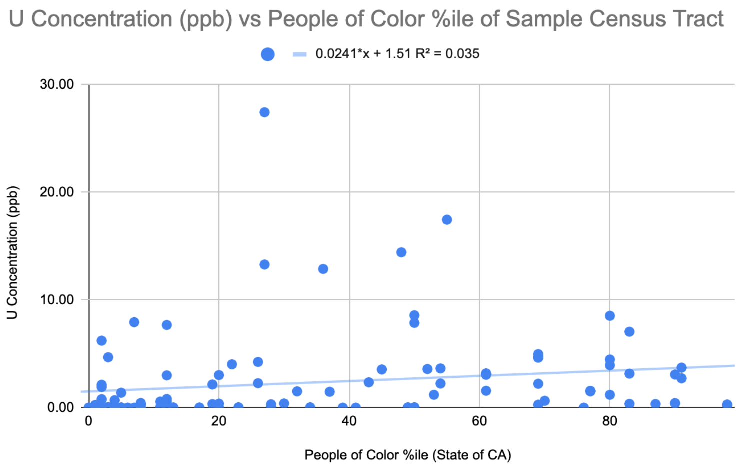
Participants with Spanish as their language preference had statistically higher levels of Arsenic (p = 0.035, r = 0.18), Cadmium (p = 0.005, r = 0.25), Uranium (p = 0.003, r = 0.26), and Vanadium (p = 0.004, r = 0.27). Participants from census tracts with higher Low Income Percentiles had statistically higher levels of Arsenic (p = 0.003, r = 0.26), Cadmium (p = <0.001, r = 0.37), Uranium (p = 0.001, r = 0.30), and Vanadium (p = 0.010, r = 0.22). Participants with higher People of Color Percentiles had statistically higher levels of Uranium (p = <0.001, r = 0.42) and Vanadium (p = <0.001, r = 0.43).



p-value	**r-value**
0.035	0.18



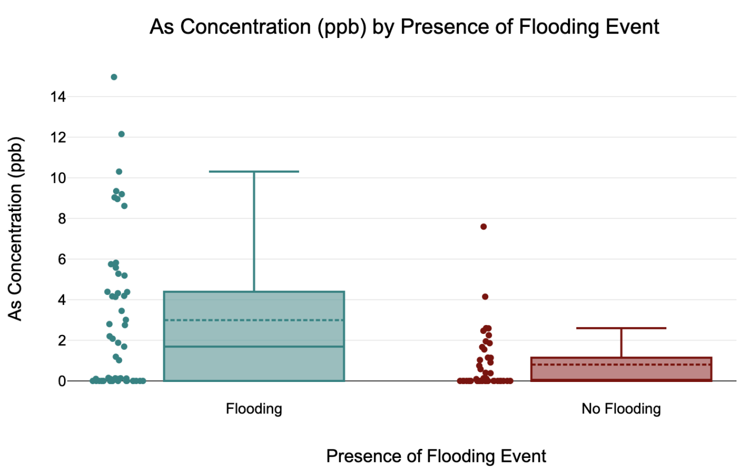
p-value	**r-value**
0.010	0.24



p-value	r-value
0.001	0.30

Figure 6: Examples of statistically significant differences and correlations for each of the parameters. Boxplot of Arsenic Concentration (ppb) by Language Preference (p = 0.035, r = 0.18); scatterplot of Arsenic Concentration (ppb) vs Low Income Percentile (State of CA) (p = 0.003, r = 0.26), and scatterplot of Uranium Concentration (ppb) vs People of Color Percentile (State of CA) (p = <0.001, r = 0.42). The middle solid line represents the median, and the dotted line represents the mean.

Participants who reported a flooding event within the last 5 years and living within a mile from the sampled well location had statistically higher levels of Arsenic (p = 0.030) and Vanadium (p = <0.001) than those who reported no flooding events. There were no statistical differences of the selected inorganic constituents between participants that reported a flooding event within the last 5 years and those living within a mile of the sampled well location. There



p-value	r-value
0.002	0.31

Figure 7: Boxplot of Arsenic Concentration (ppb) by Presence of Flooding Event ($p = 0.035$). "Flooding" was selected by participants to indicate the presence of a flooding event within 1 year of sampling and within a 1 mile radius of the well location. The middle solid line represents the median, and the dotted line represents the mean.

were no statistical differences of the selected inorganic constituents between participants that reported fertilizer or pesticide use within the last year and within 100 feet of the sampled well location. Figures demonstrating all constituent - parameter relationships of the selected inorganic constituents, both statistically and not statistically significant, are included in the Appendix.

Non-Carcinogenic Health Risk Analysis

The Hazard Quotient was calculated, which specifies values greater than 1 as posing a non-carcinogenic health risk, and values less than 1 as not posing non-carcinogenic (NC) health risk. The fraction of participating households with water quality posing some non-carcinogenic health risk is shown below in Figure 8:

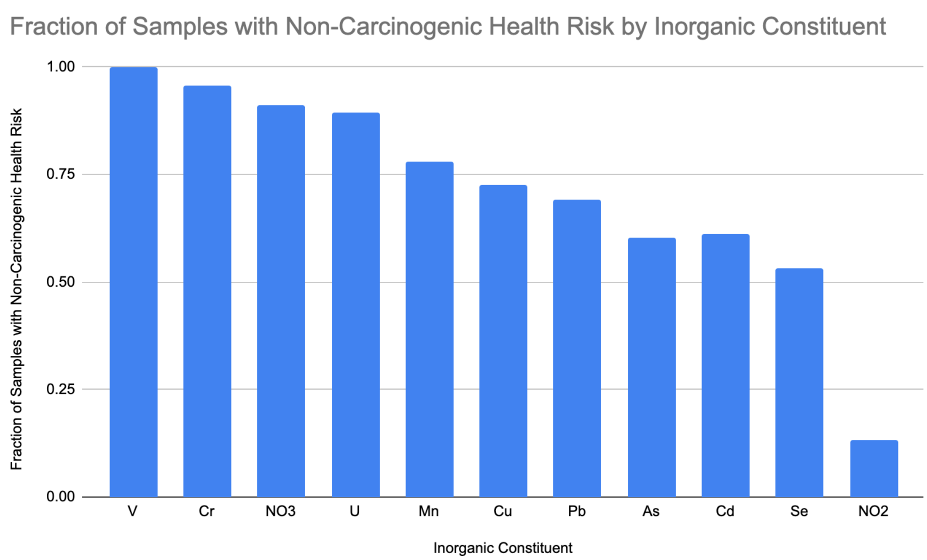


Figure 8: Bar chart of Fraction of Samples with Non-Carcinogenic Health Risk by Inorganic Constituent. The fraction indicates the proportion of samples that had a Hazard Quotient (HQ) greater 1, indicating that they posed some non-carcinogenic health risk.

Constituent	Fraction of Samples with NC Health Risk	Potential Symptoms	Source
V	1	Gastrointestinal effects, Hair loss	USEPA IRIS (2012)
Cr	0.956	Kidney/liver damage, skin irritation	USEPA IRIS (1998)
NO3	0.912	Infant methemoglobinemia	USEPA IRIS (1991)
U	0.894	Renal and developmental effects	USEPA IRIS (1989)
Mn	0.779	Neurological effects	USEPA IRIS (1995)
Cu	0.726	Gastrointestinal effects	USEPA IRIS (1988)
Pb	0.690	Neurobehavioral development in children	USEPA IRIS (2004)
As	0.602	Nausea and vomiting, shortness of breath, skin lesions	USEPA IRIS (1991)
Cd	0.611	Nausea and gastrointestinal effects	USEPA IRIS (1989)
Se	0.531	Hair loss, gastrointestinal effects, joint pain, skin discoloration, tooth loss	USEPA IRIS (1991)
NO2	0.133	Painful urination, fever, fatigue	USEPA IRIS (1987)

Table 4: Fraction of Samples with Non-Carcinogenic (NC) Health Risk by Constituent, with listed potential symptoms. Over 90% of samples posed some health risk of gastrointestinal effects and hair loss (Vanadium), kidney/liver damage and skin irritation (Chromium), and infant methemoglobinemia, or "blue baby syndrome" (Nitrate).

Discussion

To our knowledge, this study was the first to explore the comprehensive relationship between socioeconomic factors, climate change events, and land use in domestic well water quality. The recruitment methods reached participants of different socioeconomic backgrounds. Recruitment through the UC Davis Health article involved participants reaching out to our study, many of whom were from the Sierra Nevada foothills. This access to academic articles reflected a demographic with higher socioeconomic status, as indicated by the limited representation of people of color, low-income households, and non-English speakers). EJCW recruited participants in the larger Stockton region, which consisted of a wider variability of socioeconomic status, while still having significantly lower socioeconomic status (e.g. language preference, income, people of color) than the UC Davis Health article. This demonstrates that significant differences between socioeconomic factors and water quality reflect spatial disparities in California's socioeconomically heterogeneous landscape. The coupling and colocation of socioeconomically disadvantaged communities with certain geologic regions and land use areas reflected in the water quality indicate distributive injustices. This also highlights the importance of collaboration with the Environmental Justice Coalition for Water for their geographically-specific community expertise that was central to the study design and diverse recruitment.

After stratifying by parameters, participants with higher percentiles of low income census tracts and with Spanish language preferences had significantly higher levels of arsenic, cadmium, vanadium, and uranium. Participants with higher percentiles of people of color in their census tracts had higher levels of uranium and vanadium. This disproportionate exposure is an issue of distributive justice in that they have a disproportionate burden placed on socioeconomically disadvantaged communities. This, in turn, has implications for the health and financial burden placed on underrepresented and underserved communities. While many of the exceedances are produced or exacerbated by industrial land uses, the burden of high-cost water testing, remediation, and health bills are largely placed on socioeconomically disadvantaged communities. Our community recruitment partner, EJCW, shared they experienced challenges recruiting specifically migrant farmworkers, many of whom feared that receiving results of poor water quality could pose risks to their employment, threaten their housing security, or even result in deportation/legal action. This observation sheds light on important limitations in the collection of domestic well water, underscoring the importance of collaboration with environmental justice organizations with established trust and community relationships, specifically the recruitment of participants representing diverse incomes, documentation status, and racial/ethnic backgrounds.

In exploration of climate change impacts, participants that reported flooding within the last 5 years and within a mile of the sampled well location had significantly higher levels of arsenic and vanadium. This corresponds to the expected changes in arsenic and vanadium adsorption to iron oxides resulting from the altered redox conditions produced by flooding. Flooding can increase infiltration of carbon-rich waters into groundwater, resulting in a high oxygen demand and increased reduction potential. This, in turn, can mobilize solid iron (oxy)hydroxides, responsible for the adsorption of arsenate and vanadate, and further mobilizing the arsenic and vanadium into the aqueous phase. There were no significant differences in wildfire, fertilizer, and pesticides, which could point to the need for a more localized consideration of groundwater residence times.

While most of the samples had no exceedance of Primary MCL, all samples had some health risk associated with the constituent levels. Of the hazard quotient calculations, vanadium had the largest impact, posing a non-carcinogenic health risk for 113 (100%) samples, including lung irritation, shortness of breath, and asthma-like symptoms. Next was uranium, which posed a health risk for 104 (92.0%) samples, including respiratory illness, reproductive/developmental problems, and renal failure. cadmium was next, with 69 (61.1%) samples at risk of decreased bone density and stomach problems. Lastly, arsenic posed some health risk for 68 (60.2%) samples, which included nausea and vomiting, shortness of breath, and skin lesions [21].

Exploring carcinogenic health risks are an important next step to quantifying the holistic health risks associated with drinking water from domestic wells.

Conclusion

This study is among the first to cumulatively assess the relationship between social disparities, climate change implications, and land uses on inorganic constituents in California domestic well water. Although only five (4.4%) of the samples had exceedances of enforceable drinking water standards for arsenic, cadmium, uranium, and vanadium, 113 (100%) demonstrated non-carcinogenic health risks for these same constituents. Our results suggest that low-income communities and Spanish speaking communities may have disproportionate exposure to arsenic, cadmium, uranium, and vanadium. Communities of color were also found to have disproportionately high levels of uranium and vanadium. Locations that experienced flooding within five years of sampling and one mile from the well site had significantly higher levels of arsenic and vanadium. With the increasing hydrologic intensification and flooding resulting from climate change, elevated levels of inorganic constituents are expected to occur with increasing frequency. In order to address the State of California's goal of protecting the Human Right to Water, there is a need for a commitment to expanded domestic well water monitoring that democratizes data produced in laboratories, engages community expertise in localized problem solving, and offers affordable remediation solutions, with specific attention to underserved and underrepresented communities. There also remains a need for temporal sampling, analysis of organic constituents, a list of filters that are certified for the remediation of certain constituents, state/corporate financial support for remediation, and precautionary monitoring for constituents with concentrations below the enforceable drinking water standard but above the lowest observed adverse effect level to inform communities of the potential health risks of drinking their well water.

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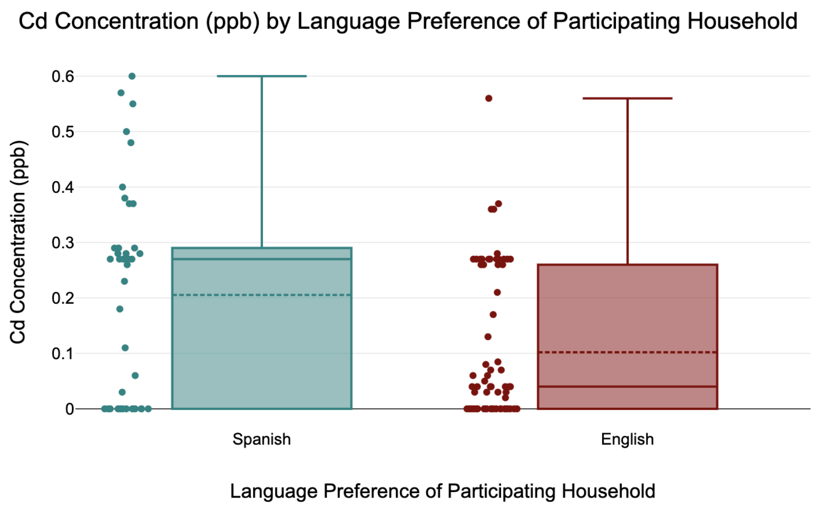
Appendix



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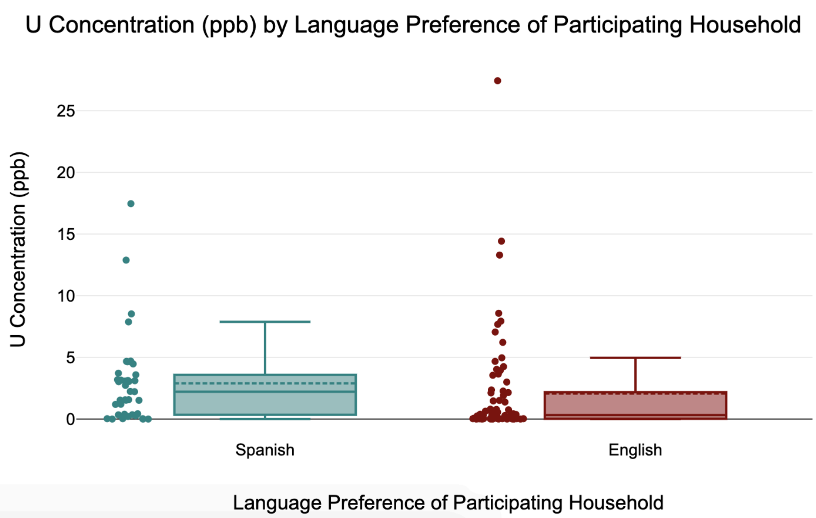

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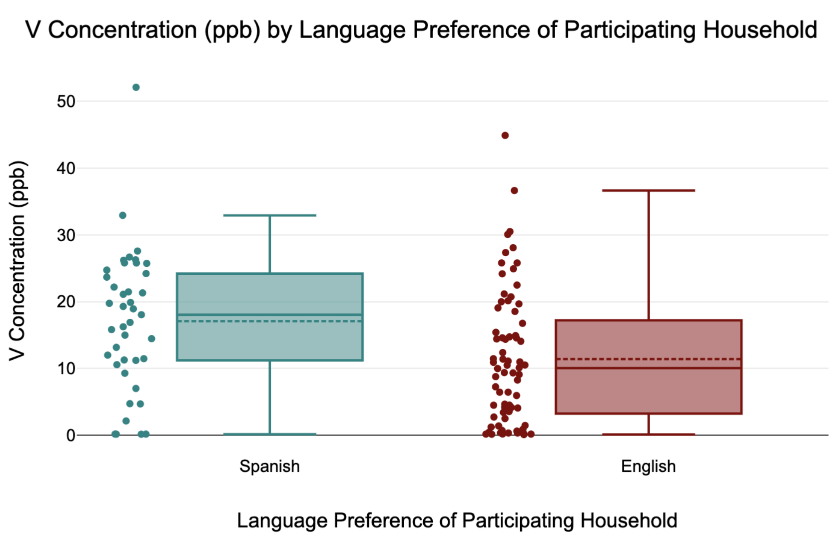

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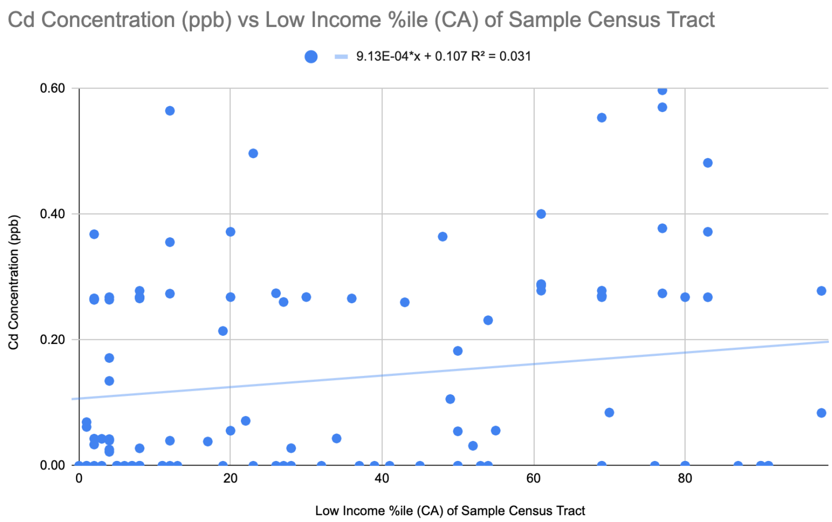

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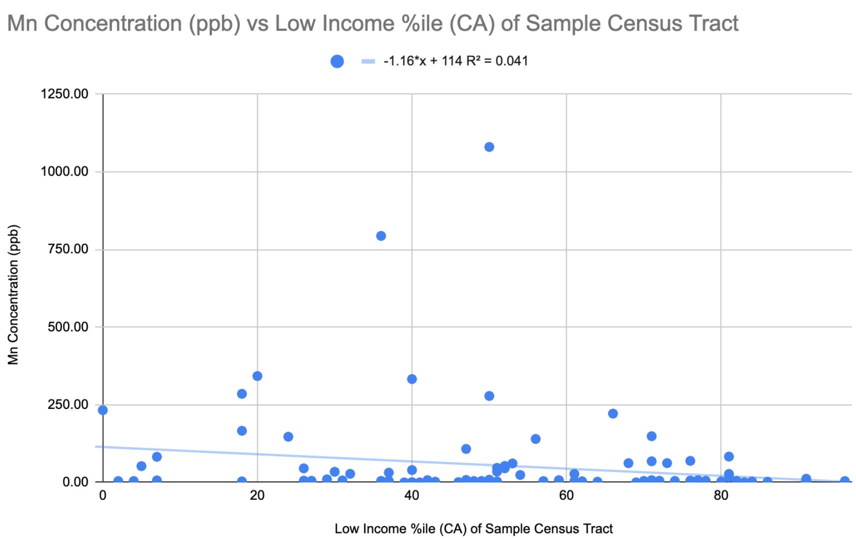

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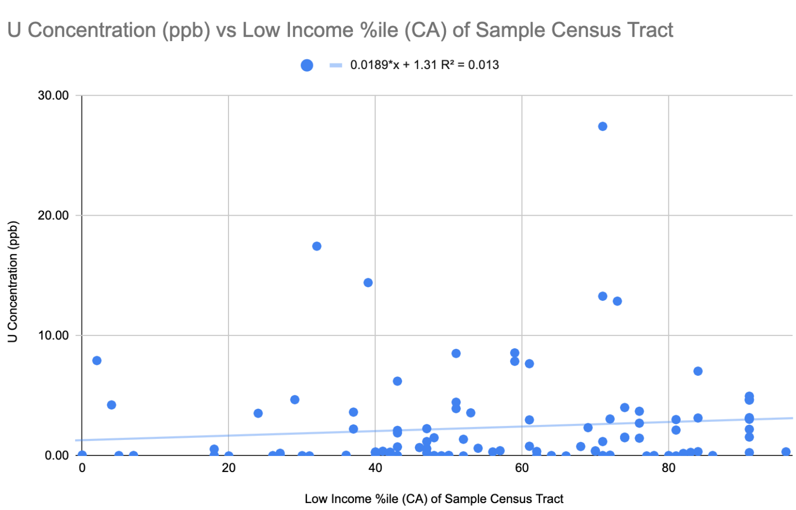

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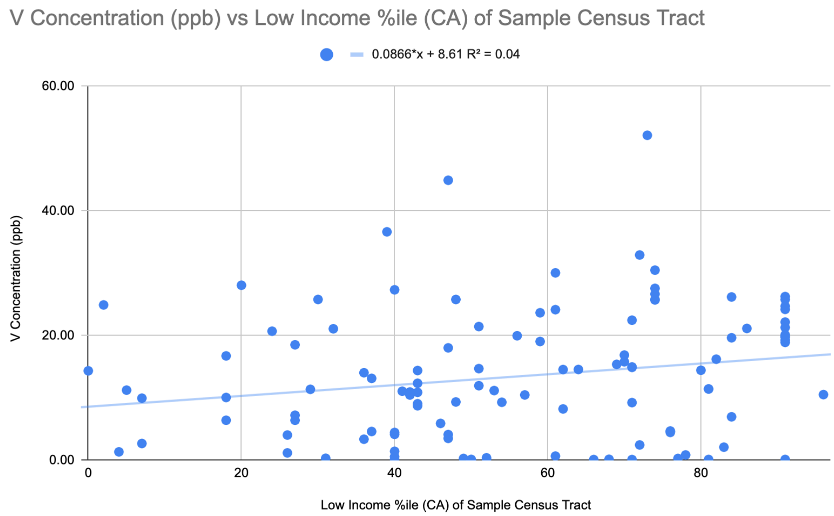

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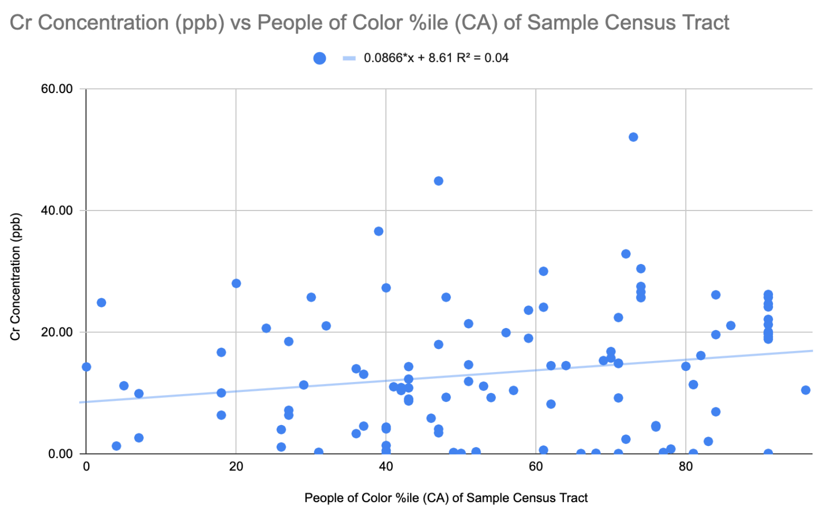

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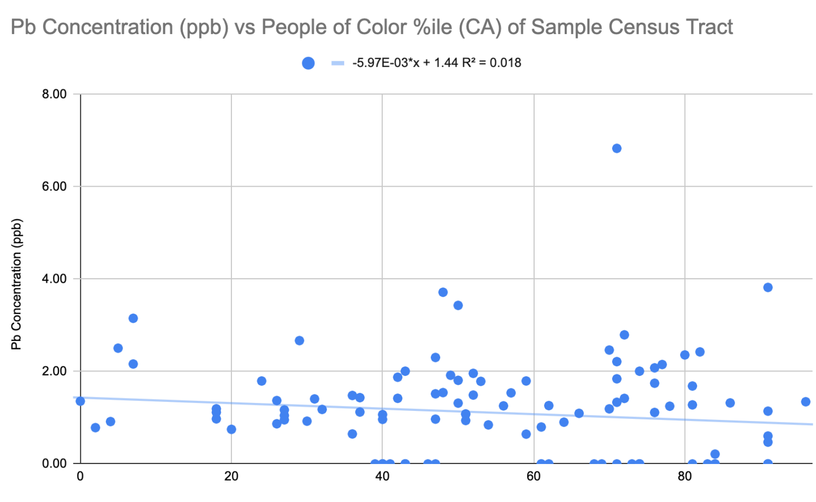

p-value	r-value
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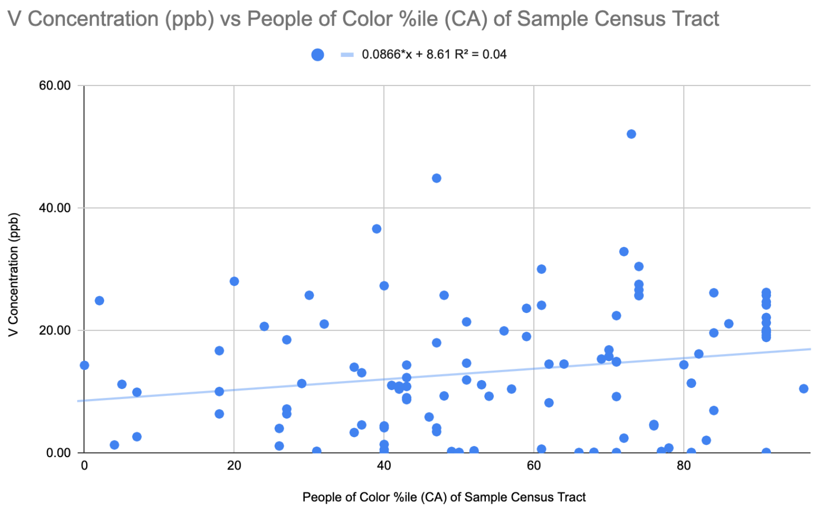

p-value	r-value
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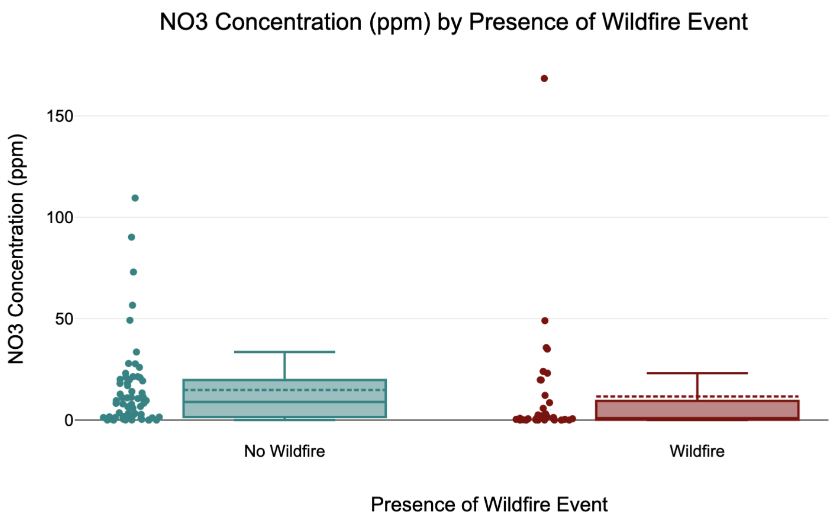

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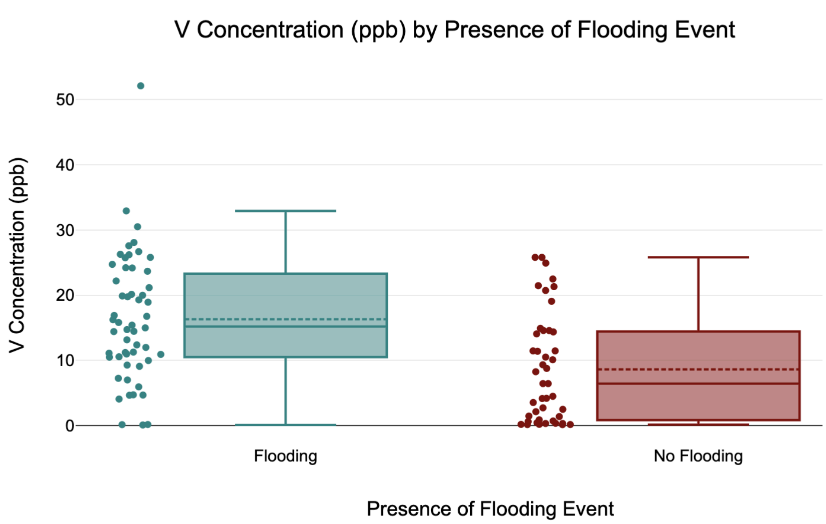


p-value	r-value
<0.001	0.39

Figure A1: Scatterplots and Boxplots of statistically significant relationships ($p < 0.05$) of **Table 3** data with p-values and r-values.

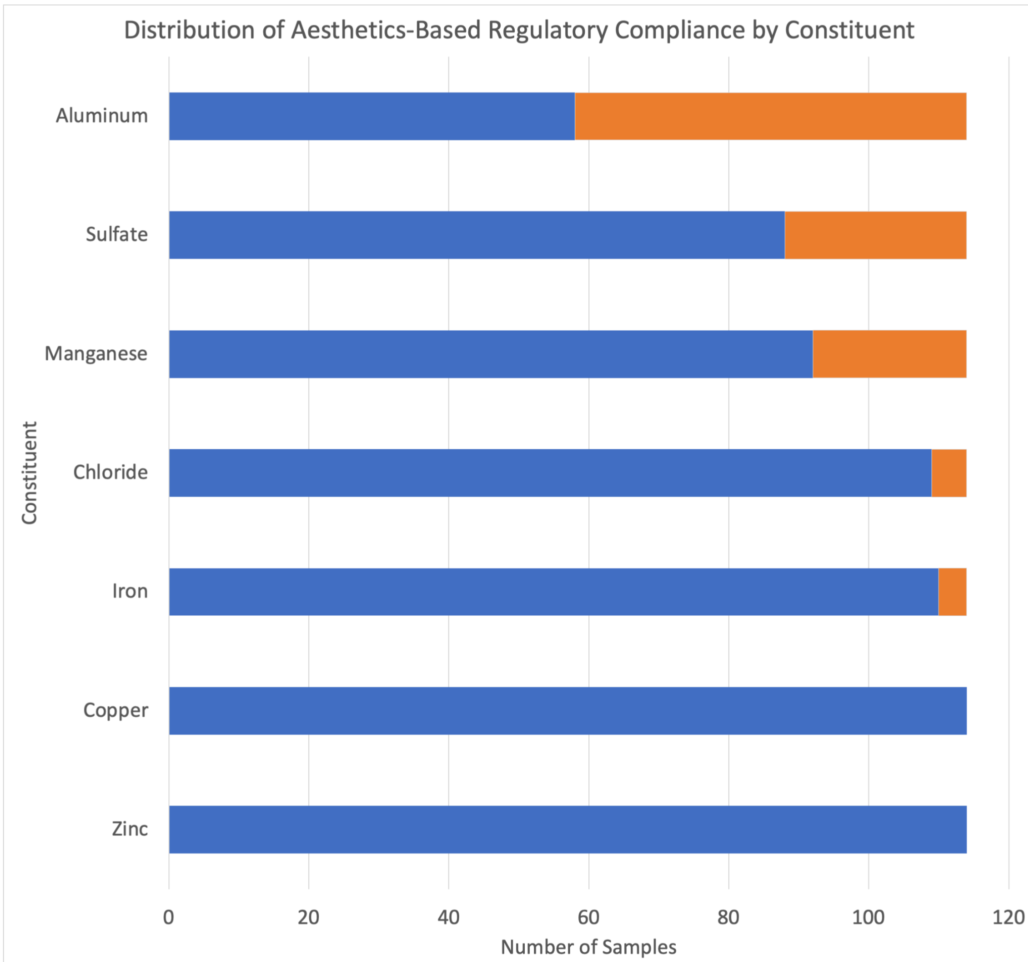


Figure A2: Distribution of Health-Based Regulatory Compliance by Constituent. The constituents with highest number of Secondary MCL exceedances included aluminum (n = 56/113, 49.6%), sulfate (n =26/113, 23.0%), manganese (n = 22/113, 19.5%), chloride (n = 5/113, 4.4%), and iron (n = 4/113, 3.5%).

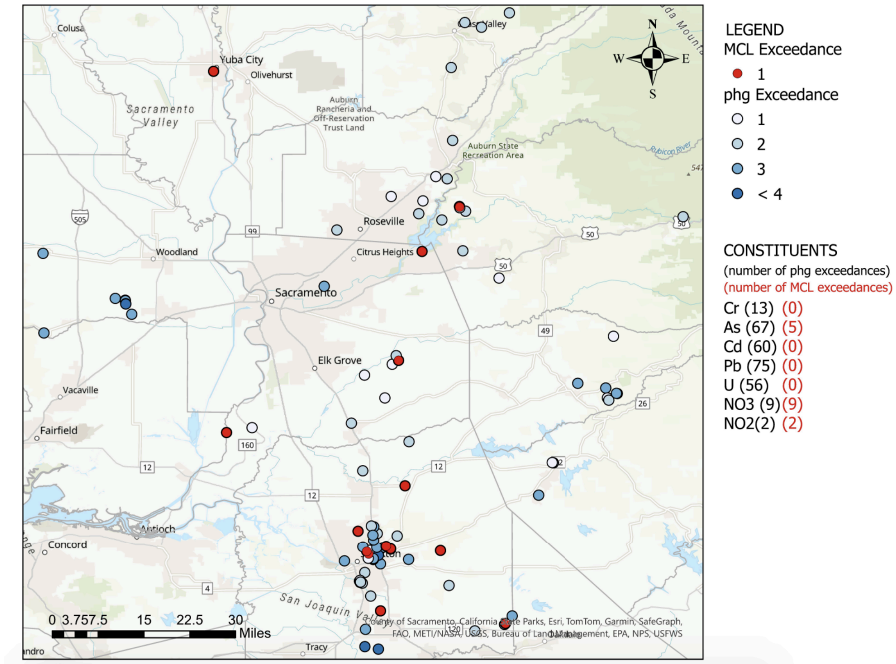
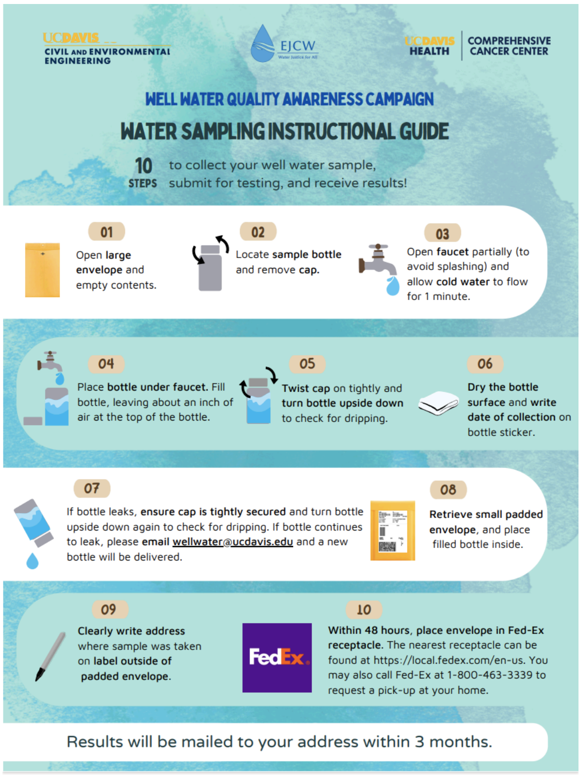


Figure A3: Map of Sample Health-Based Regulatory Compliance Spatial Distribution. Red points indicate a primary MCL exceedance, the gradient of points from dark blue to white indicate PHG exceedance(s).

Figure A4: Bilingual Recruitment Flyer for Well Water Quality Awareness Campaign (Eng/Esp), detailing eligibility requirements, participant expectations, and a gift card incentive.



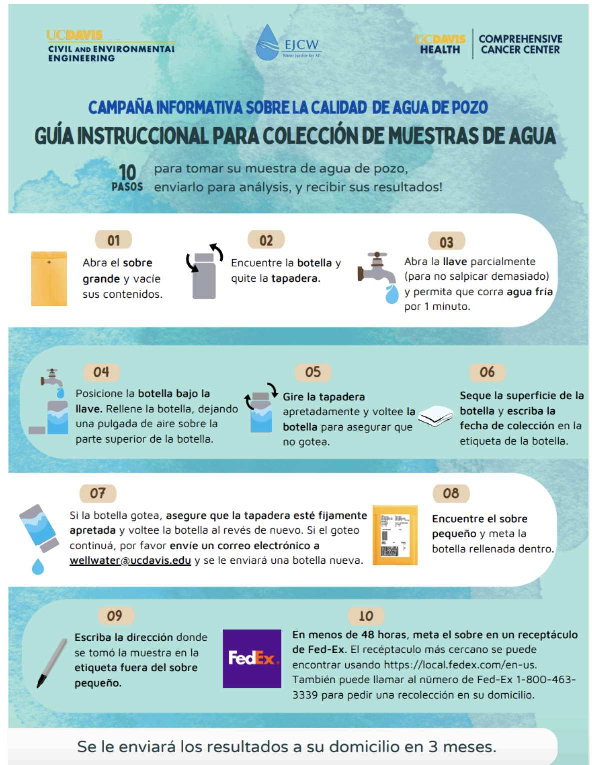


Figure A5: Bilingual Water Sampling Instructional Guide for Well Water Quality Awareness Campaign (Eng/Esp), demonstrating step-by-step graphics for sample collection, labeling, and shipping.

UCDAVIS CIVIL AND ENVIRONMENTAL ENGINEERING

EJCW Water Justice for All

UCDAVIS HEALTH | COMPREHENSIVE CANCER CENTER

Residents of [redacted]
Stockton CA 95212

SAMPLE REPORT

October 03, 2023

Dear Resident,

Thank you for taking part in this well water quality awareness campaign. You are helping us to learn about the quality of well water in your community. Most well water in California is safe and healthy. Sometimes well water can become contaminated from natural sources or from human activities, making the water unsafe or unhealthy.

In California, public water quality is regulated by both Federal and State standards. The United States Environmental Protection Agency (EPA) sets a ***Maximum Contaminant Level (MCL)*** for some constituents in water. An MCL is the highest level of a contaminant that is allowed in drinking water. Levels above the MCL violate the EPA standards developed to protect public health. In addition to these MCLs, California also sets ***Action Levels*** for lead and copper and notification and ***Response Levels*** for manganese and vanadium. Water with levels above the Action Level or Response Level signal the need for additional treatment or actions. Lastly, many contaminants that have drinking water standards also have ***Public Health Goals (PHG)***. Contaminant levels below the PHG have no known health risks.

Currently, California does not require testing of private groundwater wells. Well water users are responsible for testing their own water. Well water users are also responsible for taking action when a contaminant is above the MCL, Action Level, or Response Level. On the next page, we provide you with the results for the tests that we conducted at UC Davis on the water sample you collected from your home. We have included the MCL, Action Level, or Removal Level for contaminants that have established values. We have also included the PHG for contaminants.

We have a list of resources on our website that you can use to learn more about well water safety and treatment options if you are concerned about the quality of your well water. You can visit our website using the QR code to the right. If you have any questions about this study, please feel free to contact us at wellwater@ucdavis.edu.

QR Code: Open your Camera app on your mobile phone and point it steadily for 2-3 seconds towards the QR Code

Sincerely,

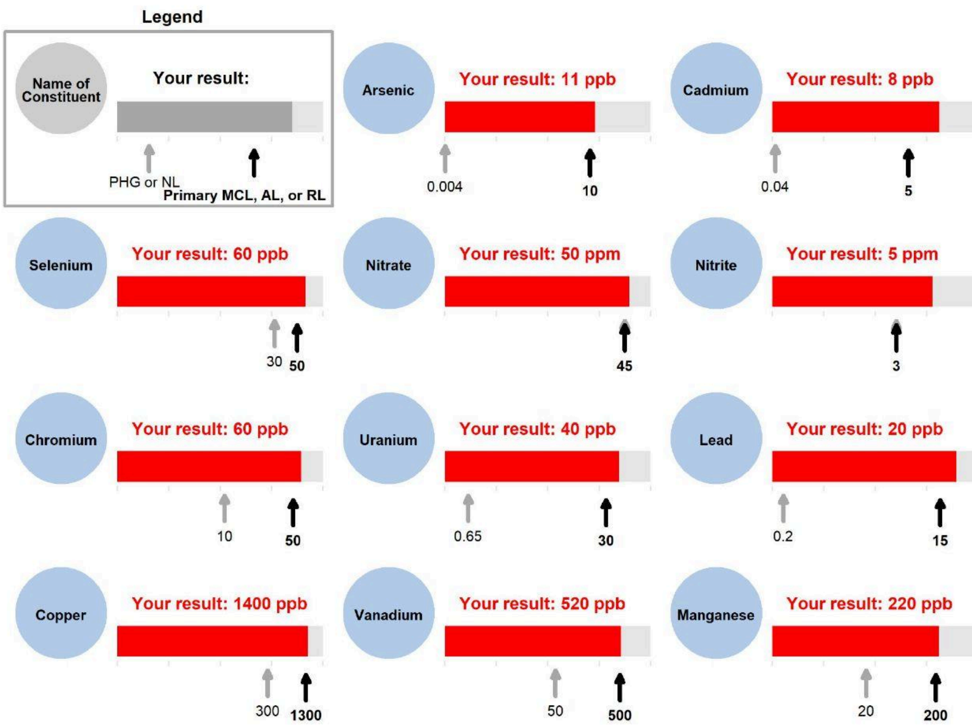
Shehnaz Hussain, PhD
Professor
Department of Public Health Sciences

Jasquelin Peña, PhD
Associate Professor
Department of Civil and Environmental Engineering

Your Well Water Test Results

Below we provide a summary of the constituent levels in your well water samples. The constituent levels are reported either in units of parts per billion (**ppb**) or part per million (**ppm**). When the constituent was 'not detected', we report N.D.

First, we show you constituents with a **health-based** regulatory limit, Action Level or Notification and Response Level. The bar graph indicates if your sample is **above** or below the regulatory level[1] or the action or response level[2]. We also indicate the Public Health Goal[3] for each constituent. See the footnotes below the graphic for definitions.



[1]Regulatory levels are defined by a **Maximum Contaminant Level (MCL)**. These drinking water standards consider the chemicals' health risks as well as other factors, including detectability, treatability and cost of treatment. **Primary MCLs** address health concerns and include arsenic, cadmium, selenium, nitrate, nitrite, uranium and chromium. **Secondary MCLs** address esthetics like taste and odor.

[2]Some constituents are not regulated but have a health-based **Action Level (AL)** or **Notification Level (NL)** and **Response Level (RL)**. Action levels exist for lead and copper. Response levels exist for vanadium and manganese. At levels above the response level, action to remove the contaminant from the source water is recommended.

[3]**Public Health Goals (PHG)** are established by the Office of Environmental Health Hazard Assessment. These define contaminant levels that pose no significant health risk if consumed for a lifetime, based on current risk assessment principles. Health & Safety Code §116365(a) requires a contaminant's MCL to be established at a level as close to its PHG as is technologically and economically feasible.

In the table below, we show you constituents with an **esthetics-based** regulatory limit. The last column indicates if your sample is **above** or **below** the regulatory level[4]. See the footnote for more information.

Constituent	Your water	Secondary MCL	Above or below MCL?
Iron (ppb)	17.43	300	Below
Manganese (ppb)	220	50	Above
Zinc (ppb)	6.38	500	Below
Copper (ppb)	1400	1000	Above
Aluminum (ppb)	263.66	200	Above
Chloride (ppm)	22.45	250*	Below
Sulfate (ppm)	21.26	250*	Below

*Consumer accepted levels up to 500 ppm.

For other constituents we measured, there are no Maximum Contaminant Levels or Notification and Response Levels to compare to the concentrations we found in your water sample. Your results are provided here for your interest:

Constituent	Your water
Sodium (ppm)	1019
Potassium (ppm)	35.14
Magnesium (ppm)	3.44
Calcium (ppm)	8.22
Lithium (ppm)	0.33

[4]Regulatory levels are defined by a **Maximum Contaminant Level (MCL)**. These drinking water standards consider the chemicals' health risks as well as other factors, including detectability, treatability and cost of treatment. **Primary MCLs** address health concerns and include arsenic, cadmium, selenium, nitrate, nitrite, uranium and chromium. **Secondary MCLs** address esthetics like taste and odor.

Finally, we have provided some additional information for the constituents that we tested in your sample that were found to be above the MCLs or action levels.

Arsenic	
Where do these chemicals come from?	Some of the arsenic in groundwater comes from water flowing through underground aquifers. Under some conditions, water that flows through these aquifers can dissolve arsenic from arsenic-bearing minerals. Arsenic can also come from industrial and agricultural activities, for example, animal feeding operations and fertilizers. The arsenic used in these activities can enter the groundwater by moving with the flow of water from rainwater.
Why might these chemicals be a health concern?	Arsenic has been associated with short- and long-term health effects. Short term effects include stomach pain, numbness of the hands and feet, skin discoloration, and thickening of the skin. Long term effects include cancer, high blood pressure, effects on the nervous system, some respiratory illnesses, and Type 2 diabetes.
How can I reduce my exposure?	One way to reduce arsenic exposure is to use bottled water for drinking and cooking. There are also water treatment devices that can filter arsenic from water. The State of California keeps a list of water treatment devices that can remove arsenic from drinking water. More information can be found at: https://health.ucdavis.edu/cancer/population-health/population-health-water-quality-awareness.html.

Cadmium	
Where do these chemicals come from?	Cadmium is used in a variety of products, including batteries, metal coatings, and plastic. A common way for cadmium to enter groundwater is from water draining through a landfill. This groundwater can end up in wells used for drinking water. Mining is another source of cadmium in the environment. Cadmium is released into the environment during smelting (smelting is the extraction of metal from its ore). Once in the environment, cadmium moves through soil and water and can enter eventually reach the groundwater that is used for drinking.
Why might these chemicals be a health concern?	Long-term exposure to cadmium may lead to kidney disease, bone problems, and cancer.
How can I reduce my exposure?	One way to reduce cadmium exposure is to use bottled water for drinking and cooking. Many water treatment technologies also remove cadmium from water. More information can be found at: https://health.ucdavis.edu/cancer/population-health/population-health-water-quality-awareness.html.

Chromium	
Where do these chemicals come from?	Chromium is found naturally in rocks, plants, and soil, and can be released into water from the erosion of naturally occurring chromium deposits. A variety of industrial activities can release chromium into water; these activities include the manufacturing of textile dyes, wood preservation, leather tanning, and anticorrosion coatings. Chromium can also end up in water when an industrial site does not practice safe waste disposal methods.
Why might these chemicals be a health concern?	Possible health concerns from exposure to chromium include stomach and gastrointestinal cancers, reproductive effects, and potential damage to the liver and kidneys.
How can I reduce my exposure?	One way to reduce chromium exposure is to use bottled water for drinking and cooking. There are also many water treatment devices (for example reverse osmosis) that can remove chromium from water. More information can be found at: https://health.ucdavis.edu/cancer/population-health/population-health-water-quality-awareness.html.

Uranium	
Where do these chemicals come from?	Some uranium in drinking water comes from rocks and soil that contain minerals hosting small amounts of uranium. When water flows through the rock and soil it can dissolve these minerals resulting in uranium in the water. This water often ends up in aquifers and becomes drinking water. Other sources of uranium include the production and use of phosphate fertilizers, and mining and industrial processing activities. Uranium can end up in groundwater from runoff of these activities.
Why might these chemicals be a health concern?	Uranium exposure has been associated with liver, bone, and kidney damage. Uranium exposure has also been associated with cancer.
How can I reduce my exposure?	One way to reduce uranium exposure is to use bottled water for drinking and cooking. Many water treatment technologies also remove uranium (and radium) from water. More information can be found at: https://health.ucdavis.edu/cancer/population-health/population-health-water-quality-awareness.html.

Lead	
Where do these chemicals come from?	The most common source of lead in drinking water is from the corrosion of plumbing materials that contain lead (for example, pipes that contain lead). Corrosion is the dissolving away of a metal caused by a chemical reaction between water and the plumbing pipes.
Why might these chemicals be a health concern?	Young children and infants are particularly vulnerable to lead exposure. Health effects in children can include behavior or learning problems, lower IQ, and hyperactivity, slowed growth, hearing problems, and anemia. Lead can also lead to reduced growth of the fetus and premature birth in pregnant women.
How can I reduce my exposure?	One way to reduce lead exposure is to use bottled water for drinking and cooking. The State of California keeps a list of registered water treatment devices that can remove lead from drinking water. More information can be found at: https://health.ucdavis.edu/cancer/population-health/population-health-water-quality-awareness.html.

Selenium	
Where do these chemicals come from?	Selenium is used in several industries, including the electronics industry. Selenium may be present in plastics, paints, inks, and rubber. Selenium may also be used as a feed additive for poultry and livestock and in some pesticide formulations. Selenium from these sources can enter groundwater by gradually moving with the flow of water from rainwater, eventually ending up in wells used for drinking water.
Why might these chemicals be a health concern?	Selenium is a trace mineral needed in small amounts to maintain good health. However, at high levels it can lead to health problems affecting the heart and brain. Other health concerns include brittle hair and deformed nails.
How can I reduce my exposure?	One way to reduce selenium exposure is to use bottled water for drinking and cooking. Many water treatment technologies also remove cadmium from water. More information can be found at: https://health.ucdavis.edu/cancer/population-health/population-health-water-quality-awareness.html.

Nitrate and Nitrite	
Where do these chemicals come from?	Nitrate and nitrite are found in many fertilizers and livestock feed. The nitrate and nitrite used in these products can enter the groundwater by moving with the flow of water from rainwater and eventually end up in wells used for drinking water. Other sources of nitrate and nitrite in water are animal and human waste. Animal waste comes from industries like dairy farming; human waste can come from septic tanks and sewer systems. Nitrate and nitrite produced by these activities can enter the groundwater system through leakage or runoff, eventually ending up in wells used for drinking water.
Why might these chemicals be a health concern?	In the human body, nitrate is converted to nitrite. Exposure to nitrate and nitrite has been associated with methemoglobinemia (Blue Baby Syndrome), cardiovascular effects (hypotension or low blood pressure), and reproductive effects. Some studies have found an association between nitrate exposure and cancer.
How can I reduce my exposure?	One way to reduce nitrate and nitrite exposure is to use bottled water for drinking and cooking. There are also many water treatment devices (for example, reverse osmosis or cation exchange) that can filter nitrate from water. More information can be found at: https://health.ucdavis.edu/cancer/population-health/population-health-water-quality-awareness.html.

Copper	
Where do these chemicals come from?	Copper can get into drinking water through the corrosion of plumbing pipes, faucets, and water fixtures. Corrosion is the dissolving away of metal caused by a chemical reaction between water and the plumbing pipes.
Why might these chemicals be a health concern?	Copper is needed in small amounts to maintain good health. At high levels, however, short term exposure can lead to gastrointestinal issues. Longer term exposure can lead to liver and kidney damage.
How can I reduce my exposure?	One way to reduce copper exposure is to use bottled water for drinking and cooking. Many water treatment technologies also remove copper from water. More information can be found at: https://health.ucdavis.edu/cancer/population-health/population-health-water-quality-awareness.html.

Figure A6: Sample of Water Quality Report. Reports were mailed to all participants in English or Spanish according to their language preference.