Report No. 505

A CITIZEN SCIENCE INTERNSHIP PROGRAM TO QUANTIFY RACIAL AND ECONOMIC DISPARITIES IN LEAD LEVELS IN DRINKING WATER ACROSS NORTH CAROLINA

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A Citizen Science Internship Program to Quantify Racial and Economic Disparities in Lead Levels in Drinking Water Across North Carolina

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1. Abstract

"A Citizen Science Internship Program to Quantify Racial and Economic Disparities in Lead Levels in Drinking Water Across North Carolina" (Grant #21-17-W) has four objectives: 1) characterizing lead plumbing in North Carolina, 2) mentoring underrepresented undergraduate researchers, 3) increasing public awareness and self-efficacy related to drinking water, with a focus on marginalized communities, and 4) refining a statistical model to estimate water lead levels using citizen science data.

To characterize lead plumbing in North Carolina, we engaged participants in the Crowd the Tap citizen science program. Since Crowd the Tap was started until August 8, 2023 1796 North Carolina residents have screened their home through Crowd the Tap, identifying 1989 in-home plumbing materials and 1671 service line or well casing materials, of which 32 in-home pipes and 20 service lines or well casings were leaded. Of these households, 365 had their water tested in the lab and 208 conducted at-home lead tests. Crowd the Tap identified 226 households with some detectable lead levels, seven of which were greater than 10 ppb. There were nine positive at-home lead tests.

We have recruited 43 undergraduate and post-baccalaureate research interns. We have recruited 12 Shaw University students, one student from North Carolina Agricultural and Technical University, one student from Montreat College, 28 students from North Carolina State University, and one post-baccalaureate intern. Altogether, 16 of the 43 interns have underrepresented racial or ethnic identities, and six others are people of color. Through these internships, students learned about public engagement through faith communities, community activist groups, community-based health organizations, and in their own communities.

To increase public awareness and self-efficacy, we engaged people through various partnerships, which ensured that we engaged people of diverse backgrounds. We recruited 828 university students, 480 households connected to university interns, 296 households from high schools, 26 from faith communities, 21 from a corporate volunteer program, 31 from the Southeastern Wake Adult Day Center (a community-based health organization that supports primarily low-income Black residents of Wake county), and 109 households came to the project independently. Altogether, we recruited 969 White households, 238 Black or African American ones, 109 Asian, 71 Hispanic or Latino, three American Indian or Alaska Native, one Native Hawaiian or Other Pacific Islander, and 231 households with two or more races or ethnicities present.

We are using the citizen science data collected from Crowd the Tap to test a Bayesian Belief Network (BBN) model to predict lead levels in household drinking water. Preliminary results indicate that water quality test strips have high degrees of error and that the BBN has low predictive performance for predicting lead levels in drinking water. Our analysis is ongoing, and we are continuing to explore BBN's predictive ability for a range of samples.

Thus, Crowd the Tap has made significant progress towards each of these objectives. These results can provide guidance to utility companies seeking to prioritize areas for lead infrastructure removal that prioritize equity. Furthermore, our program has supported the professional development of undergraduate researchers from Historically Black Colleges and Universities and/or have underrepresented identities.

2. Acknowledgments

We acknowledge Dr. Marc Edwards, Dr. Siddhartha Roy, and Rebecca Kriss at Virginia Polytechnic Institute and State University; Dr. Kelsey Pieper at Northeastern University;, Dr. Adrienne Katner at Louisiana State University; and Dr. Michelle Scherer at University of Iowa for their role on the “Untapping the Crowd: Consumer Detection and Control of Lead in Drinking Water” Environmental Protection Agency grant that initially helped found Crowd the Tap. Dr. Jeff Parks at Virginia Tech University conducted the laboratory analyses for this project. We also acknowledge several project managers have helped mentor project interns and manage partnerships with various organizations: Imani Bell, Lisa Lundgren, Veronica Bitting, Deja Perkins, Nicole Esch, Emma Zawacki, and Dr. Dani Lin Hunter.

We acknowledge our partners at various organizations that helped us recruit households to Crowd the Tap including Veronica Bitting at Southeastern Wake Adult Day Center, Nicole Johnson at the North Carolina Council of Churches; Dr. Darlene Cavalier, Daniel Arbuckle, and Roland Moundalak at SciStarter; Bridget Phifer at Living Better Life Now; Dr. Zakiya Leggett at North Carolina State University; Verizon’s corporate volunteer program; and the several high school teachers and faith community leaders who engaged their students and congregations in Crowd the Tap. Finally, we acknowledge the thousands of people who took time to participate in Crowd the Tap.

We also acknowledge the 43 undergraduate and post-baccalaureate interns who helped engage households through Crowd the Tap and assisted with data analysis: Demaris Surratt, Sarah Rachita, Chetna Kumari, Aakarshit Mahajan, Zariah Ingram, Evelia DeSantis, Lauren Willhite, Daniel Lee, MacKenzie Ingle, Jasmine Hope, Rebecca Greene, Chandler Parrish, Briany Santos, Caitlyn Bell, Brian Ngo, Brett Russell, Seana Finn, Destini Phifer, Michael Ndombe, Marlon Cruz, Stephen Bulluck, Jesse Barnes, Zaid Steele, Jameliah Pinder, Haley Clayborne, Sophie Chamberlain, Amit Sen, Trevor Phelps, John Mark Polk, Keely Aldrich, Elise Walker, Tanaka Madenyika, Nhaturie Atkinson, Samuel Holdsclaw, Savanah Buck, Jasmine Hayden-Lowe, Deana Poteat, Morgan Starnes, Anusha Dasanayaka, Gabrielle Henry, Madjiguene Pene, Daniel Mattyasovsky and Matilde Strocchi.

3. Introduction

Across the globe, one hallmark of urbanization is infrastructure to treat and transport safe drinking water from sources to homes (McDonald et al. 2014). Yet, degrading infrastructure is a threat to drinking water quality (Levin et al. 2002). Lead-bearing infrastructure for transporting water is a common source of lead exposure and can detrimentally affect development, behavior, hearing, and speech, especially in children (Mayans 2019; Needleman 2004). Lead pipes were the primary type of pipes laid in the early 1900s because they were malleable and affordable. Furthermore, lead soldering was used in copper and steel pipes as late as 1986 when the Safe Drinking Water Act banned the incorporation of lead into any parts of water service lines (e.g., pipes, soldering, connectors; US EPA 1986).

Over the years, lead pipes have been replaced, but little is known about the locations where they remain. In 2016, the American Water Works Association surveyed utilities and estimated there are 6.1 million lead service lines present in the United States, which roughly serve between 15 and 22 million people (Cornwell, Brown and Via 2016). There have been no large-scale surveys or estimates of leaded plumbing remaining in households. Despite efforts to identify these service lines, there remains a coarse-grained understanding of the spatial patterns of the distribution of risk of lead in drinking water. Through Crowd the Tap, we crowdsourced data on drinking water infrastructure within households.

According to the North Carolina Department of Environmental Quality, 97% of North Carolina counties have at least one community water system with leaded infrastructure that collectively serves 10 million people. Twenty percent of counties report that 80% or more of their water systems have lead. Yet, like the United States more broadly, water systems do not have records with sufficient details to identify high risk areas at finer spatial scales, and almost nothing is known about service lines on the private portions of property and plumbing on household premises. This prevents North Carolina water utilities from properly managing lead levels and residents across the state from making decisions to ensure their families are protected.

While the health effects of lead poisoning make the uncertainty of lead plumbing locations problematic for all residents of the state, lead plumbing may more disproportionately affect low income and/or communities of color. While studies on social determinants of lead are limited, previous research has demonstrated that leaded water infrastructure can disproportionately affect communities of color, renters (Balazs et al. 2011), rural communities (Allaire, Wu and Lall 2018; Marcillo and Krometis 2019), and those without insurance (McDonald and Jones 2018). That said, more research is needed to examine the potential disproportionate exposure to people of color and low income communities (Calderon et al. 1993; VanDerslice 2011). Furthermore, intentional efforts to engage diverse communities is especially important in citizen science projects that engage the public in research because it is increasingly well recognized that projects fail to attract diverse audiences (Allf et al. 2022; NASEM 2018; Pateman, Dyke and West 2021), which may hinder communities of color and low income communities from collecting the data they need to advocate for change (Blake, Rhanor and Pajic 2020; Mahmoudi et al. 2022).

To address these various needs, the Crowd the Tap citizen science project has the following research objectives: 1) characterize lead plumbing in North Carolina households, 2) provide mentored research experiences for students at Historically Black Colleges and Universities (HBCUs), 3) increase public awareness and self-efficacy related to drinking water with an emphasis on underrepresented communities, and 4) refine a statistical model to predict drinking water lead levels using citizen science data.

4. Methods

4.1. Crowd the Tap

Crowd the Tap involves two levels of participation (Figure 1). In the first level, households identify the materials that make up in-home plumbing and privately-owned service line materials and in some cases, conduct a water chemistry test strip to obtain preliminary water chemistry data. The pipe materials, preliminary chemistry data, age of the household, water aesthetics, and demographic data are then submitted online through the Crowd the Tap website. These variables are used to classify households' risk of lead contamination, according to known predictors of leaded water that were identified by Bayesian Belief Network (BBN) models (Fasaee et al. 2021, 2022).

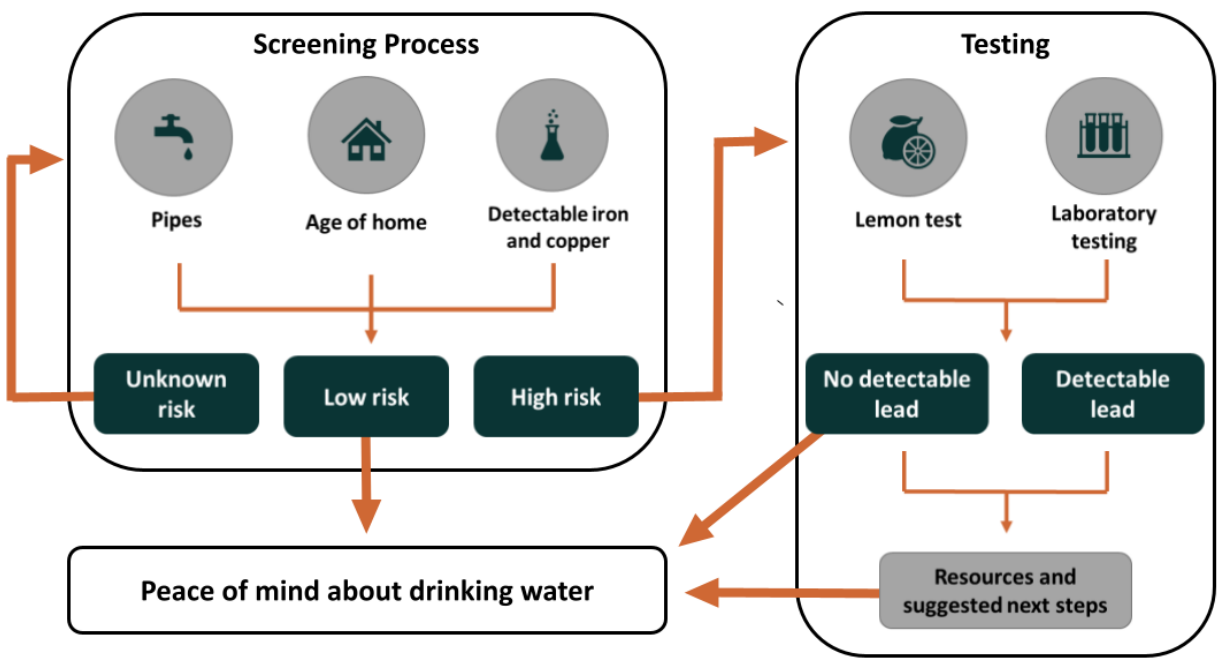

Figure 1. The Crowd the Tap Engagement Process (from Lin Hunter and Cooper, in press).

Participants can then follow up with testing their water through either laboratory testing alone or the combination of laboratory testing and an at-home lead test called the lemon test. The lemon test is a twist on conventional at-home lead tests that historically fail to detect particulate lead in water. Researchers in the lab determined that by adding lemon juice, a commonly available household acid, to water samples, they could use more affordable at-home lead tests to detect lead (Kriss et al. 2021). Through Crowd the Tap we are testing the efficacy of this method in everyday people's homes. These lemon test results are compared to inductively coupled plasma mass spectroscopy (ICP-MS) to confirm their accuracy. People who have their water tested receive report backs that include suggested next steps if their water has detectable lead. By participating in Crowd the Tap, people can gain peace of mind about their water.

4.2. Internship Program

We developed a Crowd the Tap internship program in which students from Shaw University, an HBCU in Raleigh, North Carolina, would help support engagement in Crowd the Tap. Shaw interns have supported engagement through their own personal connections, faith communities in conjunction with the North Carolina Council of Churches, various high school science classrooms across the state, and community-based organizations that support communities of color. We also developed an internship for North Carolina State University (NCSU) students in which students engaged members of their hometowns in the project. The first round of NCSU interns received research credit to compensate them for their efforts, and the second round was funded by a rebudget of North Carolina Water Resources Research Institute (WRRI) funds when the final semester of a graduate assistantship was not needed.

4.3. Engaging Diverse Communities

To engage more diverse participants, we recruited households to Crowd the Tap through facilitator organizations. Facilitator organizations are third party organizations separate from the project leadership team that engage their members in citizen science to enrich their members' experience with their own organization. The data for this study were downloaded on November 3, 2022 and included data from across the United States. We engaged 34 teachers to engage 817 student households. Teachers could participate in Crowd the Tap on two possible levels: Level 1 teachers only conducted the screening parts of the project, while Level 2 teachers conducted screening and testing (Figure 1). Level 2 teachers also received training and a stipend. We recruited seven faith communities that engaged 26 households through a partnership with the North Carolina Council of Churches. Three universities hired students and engaged students in service learning projects to reach 944 households. Two of these universities, Shaw University and North Carolina Agricultural & Technical University, are Historically Black

Colleges and Universities. We also recruited 193 households through a corporate volunteer program with Verizon.

We assessed the degree to which engaging households through these facilitators helped increase project diversity. To assess this we compared how household diversity differed between national averages for race and ethnicity (US Census Bureau 2021) and those recruited by facilitator organizations and between those who came to the project independently using chi-square tests. We also investigated how diversity differed across each of the facilitator organizations.

4.4. Statistical Modeling

The BBN is at the core of our machine learning analytics. It is a probabilistic directed acyclic graphical model, which represents the dependencies among the subset of attributes via directed arcs. A joint probability table is associated with each arc to explain the probabilistic relationship of the connected attributes. A BBN model is constructed from two components: 1) Directed Acyclic Graph (DAG), which is the structure of BBN and shows the topology of network, and 2) Conditional Probability Table, which is the parameter set of a BBN and is learned from a specific DAG. In previous research, we developed a BBN to characterize water lead levels based on input from users, such as household characteristics; observations about water taste, odor, and discoloration; and water quality parameters, including copper, pH, and hardness, reported through laboratory analysis (Fasaee et al. 2021, 2022). In the research described here, we aimed to test the performance of the BBN for predicting lead levels at households using water quality parameters reported by chemistry strips. We have quantified the error in at-home water quality tests and represented error in input variables (e.g., water quality parameters, such as copper, pH, and hardness) for the BBN model. We used water quality data from citizen scientists from Crowd the Tap as input for the BBN model and tested its performance for predicting the presence of leaded water. Our on-going analysis quantifies the effects of measurement error associated with low-resolution water quality tests on the capabilities of the BBN model for predicting lead at households.

5. Results

5.1. Crowdsourcing Risk of Lead Contamination in North Carolina

We have recruited 1796 North Carolina households from 81 of the 100 North Carolina counties since Crowd the Tap was started in April of 2019 (Table 1). Participants screened their homes by providing information on pipe materials, the age of their home, and in some cases, preliminary water chemistry information through a water chemistry strip. Participants identified a total of 1989 in-home plumbing pipe materials and 1671 service line or well casing pipe materials. Participants could select multiple materials in case their plumbing had joints that were made of different materials. For in-home plumbing, participants reported 32 lead pipes, 178 steel pipes, 355 copper pipes, 1040 plastic pipes, and 384 unknown pipes. For service line and well casing pipes, participants reported 20 lead pipes, 171 steel pipes, 181 copper pipes, 638 plastic pipes, and 661 unknown pipes (Figure 2). When reporting on the age of their home, 467 homes were built in 1986 or earlier, 915 between 1987 and 2013, 258 after 2014, and 156 households did not know when the home was built. A total of 794 households reported iron levels in their preliminary water chemistry data, 193 of which had iron levels greater than 0 ppb. Furthermore, 795 households reported copper levels in their water chemistry, 499 of which had copper levels greater than 0 ppb. This data was used to classify people by risk of lead contamination to prioritize further testing. Altogether, 440 households screened as high risk, 682 households screened as low risk, and 674 households were unknown risk.

Table 1. Recruitment by North Carolina Counties.

Alamance	10	Davie	3	Lee	6	Robeson	8
Alexander	44	Duplin	1	Lenoir	17	Rockingham	28
Alleghany	1	Durham	42	Lincoln	52	Rowan	6
Beaufort	7	Forsyth	42	Martin	3	Rutherford	3
Bladen	2	Franklin	6	McDowell	2	Sampson	4
Brunswick	5	Gaston	34	Mecklenburg	81	Scotland	1
Buncombe	12	Graham	2	Moore	9	Stanly	2
Burke	4	Granville	3	Nash	9	Stokes	2
Cabarrus	23	Greene	1	New Hanover	29	Surry	30
Caldwell	3	Greensboro	1	Northampton	1	Transylvania	2
Carteret	9	Guilford	191	Onslow	15	Union	20
Catawba	16	Halifax	1	Orange	21	Vance	3
Chatham	21	Harnett	3	Pamlico	2	Wake	619
Chowan	3	Haywood	26	Pasquotank	1	Washington	1
Cleveland	6	Henderson	4	Pender	2	Watauga	2
Columbus	1	Hoke	4	Perquimans	2	Wayne	10

Craven	51	Iredell	33	Person	2	Wilkes	1
Cumberland	25	Jackson	20	Pitt	39	Wilson	4
Currituck	1	Johnston	14	Polk	1	Yadkin	1
Dare	2	Jones	2	Randolph	63	Yancey	1
Davidson	12						

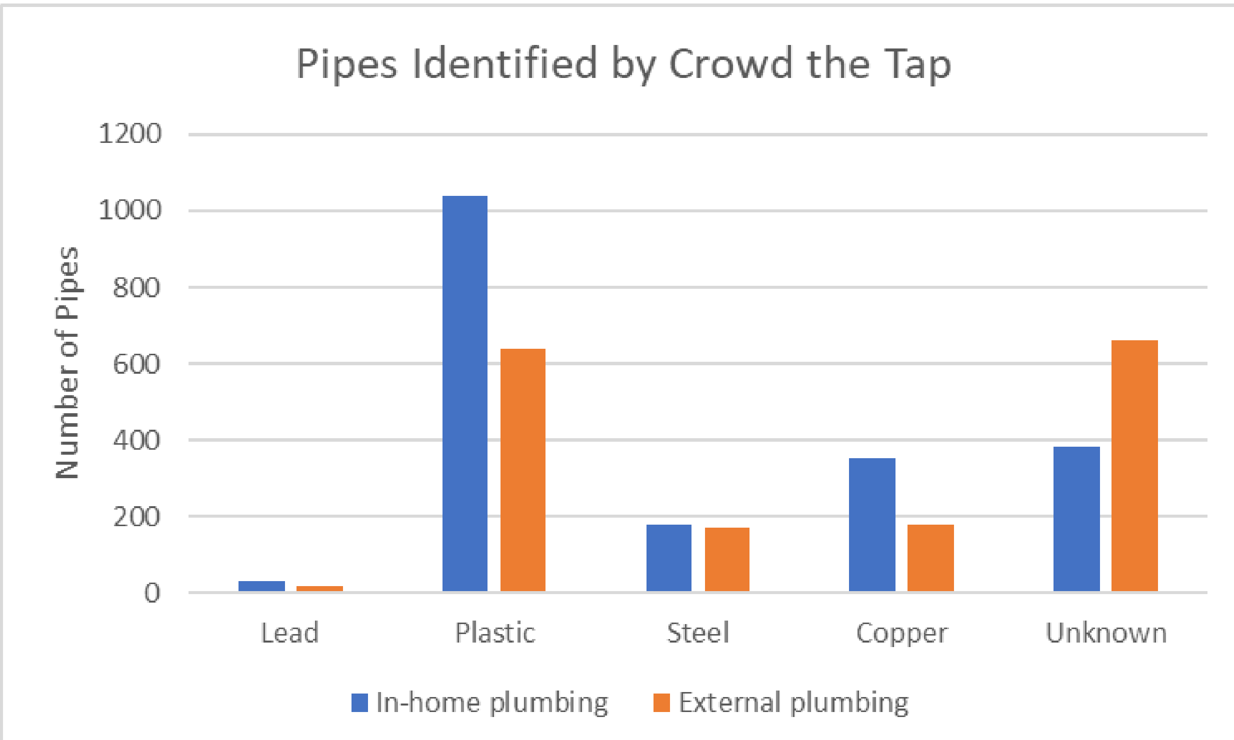

Figure 2. In-home and Service Line or Well Casing Plumbing Materials Identified through the Crowd the Tap Citizen Science Project.

5.2. Laboratory Analyses of Household Water Samples

Households who were high risk were given the option to test their water further. Low risk households could also opt into testing if they still wanted to learn more about their water. We also had a high school program in which students got their water tested regardless of their screening results. Altogether, 365 North Carolina households had their water tested in the lab and 208 at-home lead tests were conducted. Laboratory results indicated that 66 households had undetectable lead levels (< 0.1 ppb), 226 households had 0.1-1.0 ppb, 33 had 1.1-2.0 ppb, 24 had 2.1-5.0 ppb, nine had 5.1-10.0 ppb, and seven had >10.1 ppb. Of those who conducted at-home lead tests, nine were positive and 199 were negative.

5.3. Assessing the Efficacy of Crowd the Tap for Identifying Leaded Water

The results of laboratory analyses were compared to screening levels and the results of at-home lead tests in an attempt to validate them. The results from this portion of our analysis include data from across the United States (and not just North Carolina) that were collected in part from Environmental Protection Agency funding. Altogether 521 households across the United States had their water tested. Of these households, 512 could be compared back to their screening data. There were 190 high risk households, 128 low risk households, and 194 unknown risk households with both screening and laboratory data. Excluding those who screened as unknown risk, there were 318 households. When the threshold for leaded water was 15 ppb, this yielded a false positive rate of 60.6%, in which homes had been classified as high risk but did not have leaded water, and 55.6% false negative rate in which homes had been classified as low risk but had leaded water. When the threshold was 5 ppb, there was a false positive rate of 61.4% and a false negative rate of 61.1%.

Across the United States, 311 households conducted at-home lead tests. Of these households, 300 could be compared to laboratory analyses. There were 286 negative tests, 13 positive tests, and 1 inconclusive test, leaving a total of 299 conclusive test results that could be compared to laboratory data. None of the 13 positive at-home lead tests had corresponding lead measurements greater than 15 ppb, representing false positives in accordance with the test kit's stated 15 ppb threshold. The false positive rate was 4.5%. When using 5 ppb of lead as the threshold (the reported detection threshold for newer kits), there was still a 100.0% false negative rate and 4.6% false positive rate. That said, further investigation is warranted. Because high levels of lead contamination is rare, we only recruited 11 homes that had laboratory analyses indicating lead levels greater than 15 ppb, only seven of which conducted at-home lead tests (all negative). Furthermore, we only had 25 households with lead levels greater than 5 ppb, only 19 of which had conducted at-home lead tests (all negative).

5.4. Internship Program

Crowd the Tap has recruited 43 undergraduate and post baccalaureate interns to work on various aspects of the projects. We have recruited 12 undergraduate students from Shaw University, one intern from Montreat College, one intern from North Carolina Agricultural and Technical University, 28 undergraduate students from NCSU, and one post baccalaureate intern who attended the University of North Carolina at Chapel Hill and has a background as a water operator. Altogether, 16 of these interns have been underrepresented in science, and another six are people of color. We have also supported four project managers who have supervised these interns, three of whom identify as women of color and two of whom are underrepresented in science.

These interns have supported engagement through the Crowd the Tap project. They have helped reach community members in seven faith communities across the state, with three community based organizations that specifically support communities of color, and have engaged people to participate in the project in their hometowns across the state. They have also helped support engagement with teachers by putting together chemistry test strip kits and assessing quality assurance and quality control on submitted chemistry test strip data.

5.5. Engaging Diverse Communities

By November 3, 2022 when we downloaded the data to assess how well we had reached diverse households, we had recruited 2200 households to Crowd the Tap including 1250 White households, 213 Black or African American households, 191 Hispanic or Latino households, 147 Asian households, 16 Native Hawaiian or Other Pacific Islander households, three American Indian and Alaska Native households, and 270 households with two or more races or ethnicities. Another 108 households preferred not to say and two preferred to self describe. Of the multi-racial households, 246 had at least one person who was White, 129 had at least one person who was Hispanic, 82 had at least one person who was Black, 97 had at least one person who was Asian, and 23 had at least one person who was American Indian. None of the multi-racial homes included people who were Pacific Islander.

We assessed the efficacy of this recruitment through facilitators for engaging diverse participants. We used chi-square tests to compare households recruited through partnerships ($\chi^2(4) = 139.245$, $n = 3192$, $p < 0.001$) and those who participated in Crowd the Tap independently ($\chi^2(4) = 97.966$, $n = 936$, $p < 0.001$) to national average statistics to better understand how engaging households through partnerships could increase the racial and ethnic diversity represented in the project. Ultimately, our results suggest that these facilitator organizations were helpful in increasing diversity (Figure 3). We found that racial and ethnic breakdown of households whose participation was facilitated by partnerships and households who came to the project independently (unfacilitated) differed from the United States national average. White participants from facilitated households were on par with the national average while they were overrepresented in unfacilitated households. Black or African American participants from facilitated households were similar to the national average but underrepresented in unfacilitated ones. There were no differences between facilitated or unfacilitated Asian households and the national average. Hispanic and Latino homes were underrepresented in both facilitated and unfacilitated households, and households with people of two or more races or ethnicities were overrepresented for both facilitated and unfacilitated.

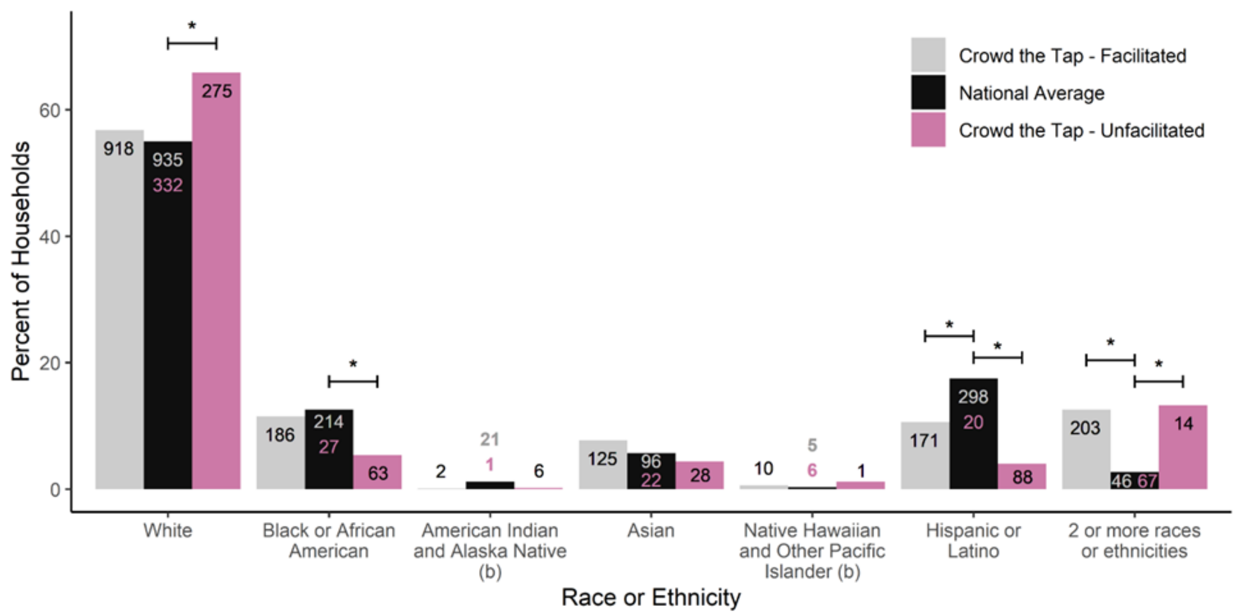

Figure 3. Racial and ethnic breakdown of Crowd the Tap households recruited independently and through facilitators (from Lin Hunter and Cooper, in press).
(a) The national average percentages sum to 95% because 0.1% of households selected Other and 4.9% selected Prefer not to say. National average percentages were taken from the US Census website and scaled to sum to 95% as well (US Census Bureau 2021).
(b) American Indian and Alaska Native households and Native Hawaiian and Other Pacific Islander households were excluded from chi-square test due to limited sample size.
(c) Data labels represent the total number of households made up of each race or ethnicity in each sample.

People of color more frequently screened their homes through facilitator groups like faith communities and classrooms (Figure 4). For example, 38.5% of Black households engaged through universities, and 10.3% of households with Black participants came from faith communities even though only 26 people total screened their homes through faith communities. Furthermore, 33.5% of households with Hispanic participants were engaged through Level 1 classrooms. The majority of Level 1 and Level 2 households with Hispanic and Black residents were less than 10% Hispanic (62.1% of classrooms; Figure 5a) and less than 10% Black (69.0% of classrooms; Figure 5b). The majority of Level 1 Hispanic diversity came from three classrooms that had >70% Hispanic students, and most of Level 2 Black diversity came from one classroom that had >80% Black students.

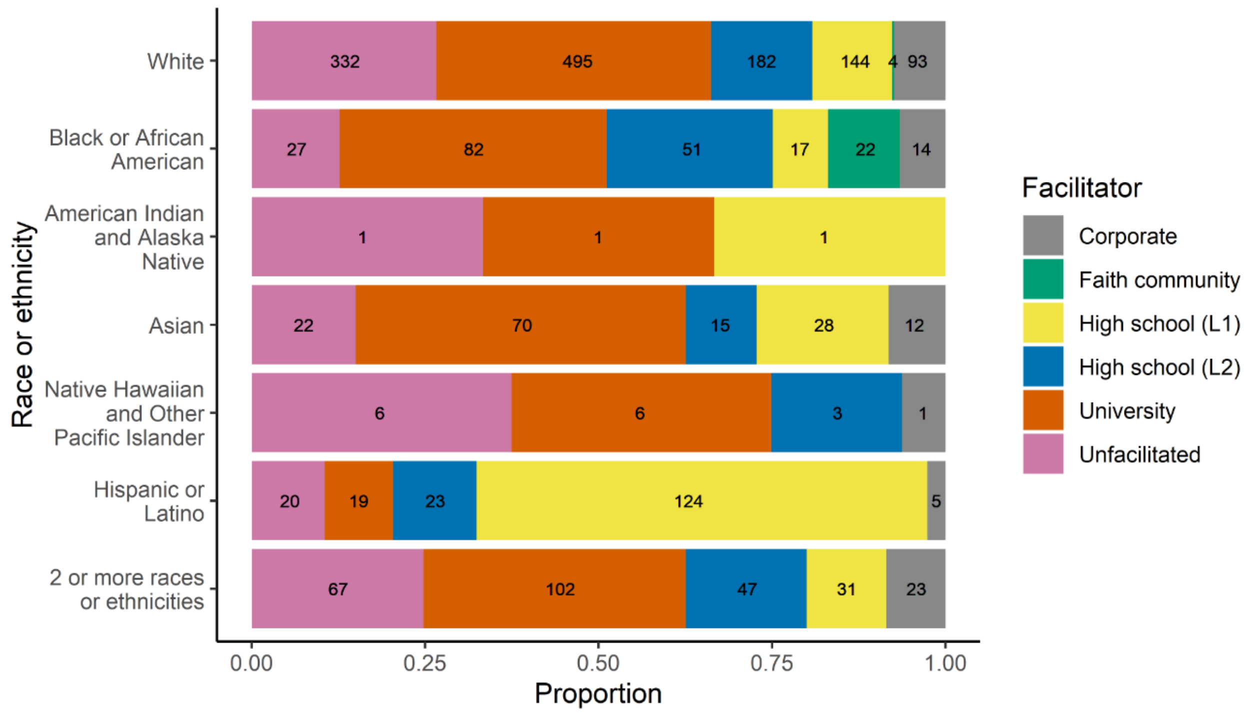

Figure 4. Proportion of each race or ethnicity by facilitator group. Data labels represent the total number of households of each racial or ethnic background that screened their homes through various facilitator organizations.

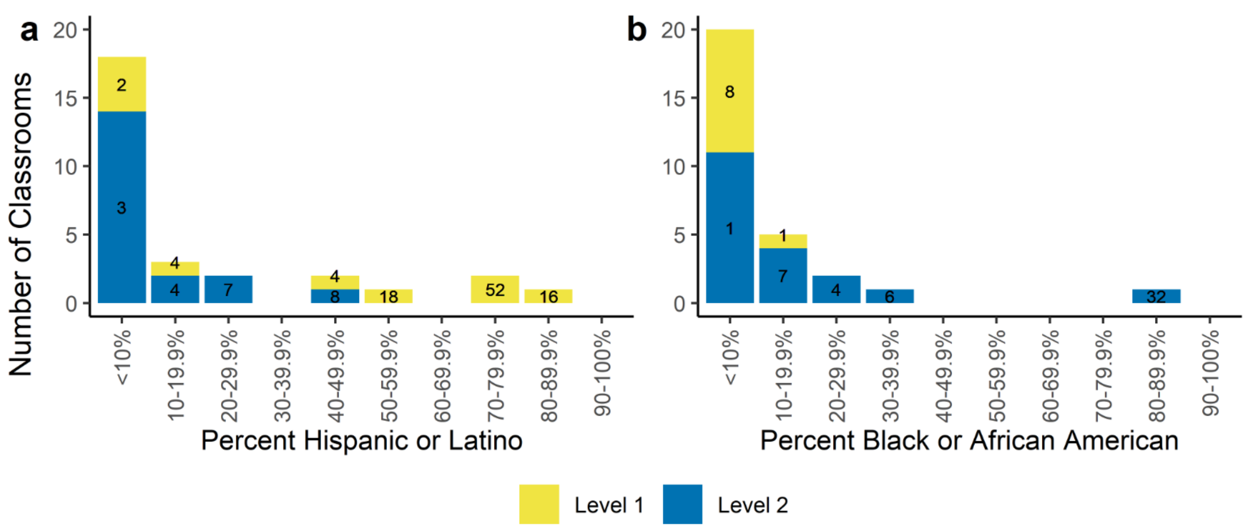

Figure 5. Number of classrooms (n = 29) with different percentages of (a) Hispanic and (b) Black students. For both races and ethnicities, a high proportion of students came from a few particularly diverse classrooms, with the majority of classrooms being composed of less than 10% Hispanic or Black students. Data labels represent the number of students of a given race or ethnicity from classrooms of each percentage category.

In North Carolina cumulatively, 1690 households have provided data on their race and ethnicity including 969 White households, 238 Black or African American households, 109 Asian households, 71 Hispanic or Latino households, three American Indian and Alaska Native households, one Native Hawaiian or Other Pacific Islander household, and 231 multi-racial households. Another 63 households preferred not to answer and five preferred to self describe.

5.6. Refining a Bayesian Belief Network Model to Predict Lead Levels from Citizen Science Data

We analyzed a set of cleaned data to assess the performance of chemistry strips to report water quality data. We used a subset of the data that included 72 samples with laboratory and chemistry strip data. Figure 6 and Table 2 shows the distribution of hardness, iron, copper, and sulfate as reported by chemistry strips. As shown here, most samples reported low levels of iron; more samples reported higher values for copper and hardness; and there was a more uniform distribution of sulfate values across the values reported by the chemistry strips.

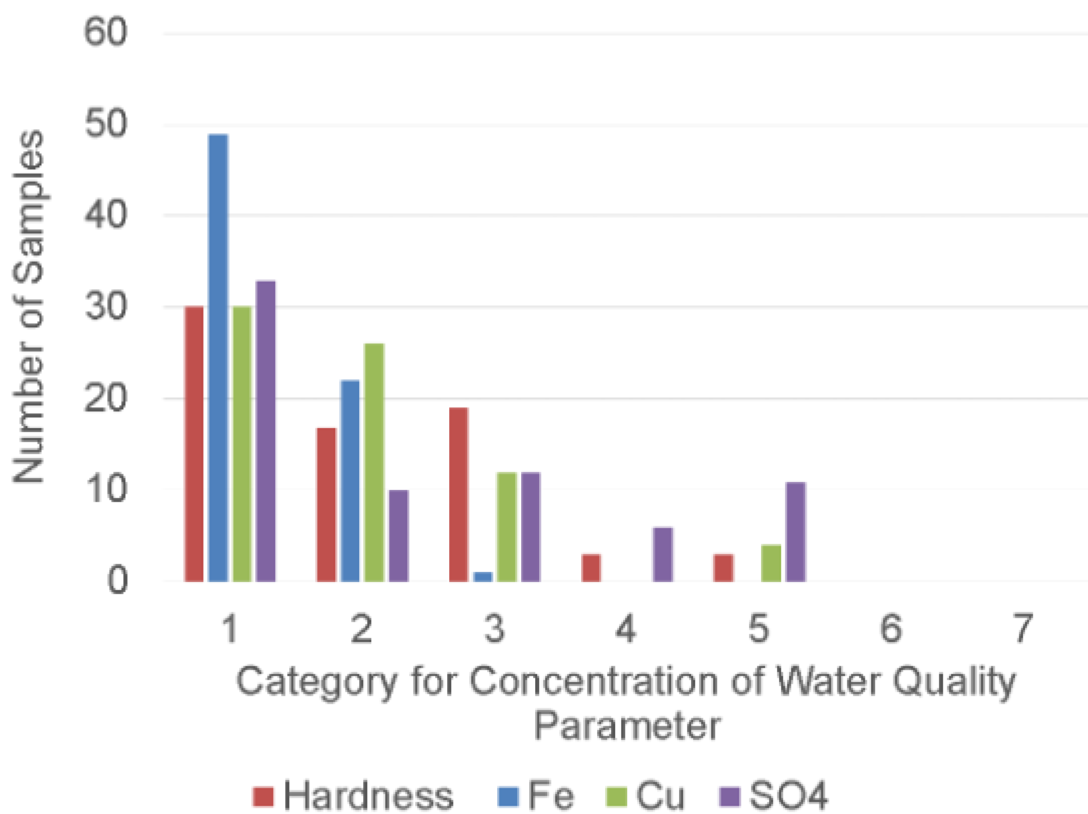

Figure 6. Histogram shows the distribution of samples collected through Crowd the Tap for water quality parameters reported using at-home water quality test kits. Definition of categories for water quality parameters are reported in Table 2.

Table 2. Water quality test kit reports four water quality parameters. Color strips report each parameter within a category that represents the concentration or presence of that parameter.

Water Quality Parameter	Category						
	1	2	3	4	5	6	7
Fe (ppm)	0-0.3	0.3-0.5	0.5-1.0	1.0-3.0	>3.0		
Cu (ppm)	0-0.05	0.05-0.1	0.1-0.2	0.2-0.4	0.4-1.0	>1.0	
Hardness	0-25	25-50	50-120	120-250	250-425	425-1000	>1000
SO4 (ppm)	0-250	250-400	400-800	800-1200	1200-1600	>1600	
Fl (ppm)	0-0.5	0.5-1.0	1.0-2.0	2.0-4.0	4.0-5.0		
pH	<6.0	6.0-6.5	6.5-7.0	7.0-7.5	7.5-8.0	8.0-8.5	>8.5

The values of iron and copper as reported by the chemistry strips were compared with the values reported through laboratory analysis. Laboratory data was converted to discrete intervals to match the units reported by the chemistry strips. Figure 7 demonstrates the performance of the chemistry strips in reporting iron. The chemistry strip reports accurate iron measurements for 44% of samples, and underreports iron for the majority of the inaccurate measurements. Figure 8 demonstrates the performance of the chemistry strip in reporting copper. Chemistry strips report accurate copper measurements for 35% of samples, and the majority of inaccurate readings underreport copper, as well. These results demonstrate high levels of error in water quality reported via at-home water quality chemistry test strips and find that chemistry strips may underestimate the concentration of water quality parameters. In these results, 72 samples were selected because they encompass the set of samples reported at the time of analysis. As samples continue to be collected and cleaned, we will continue to update these results.

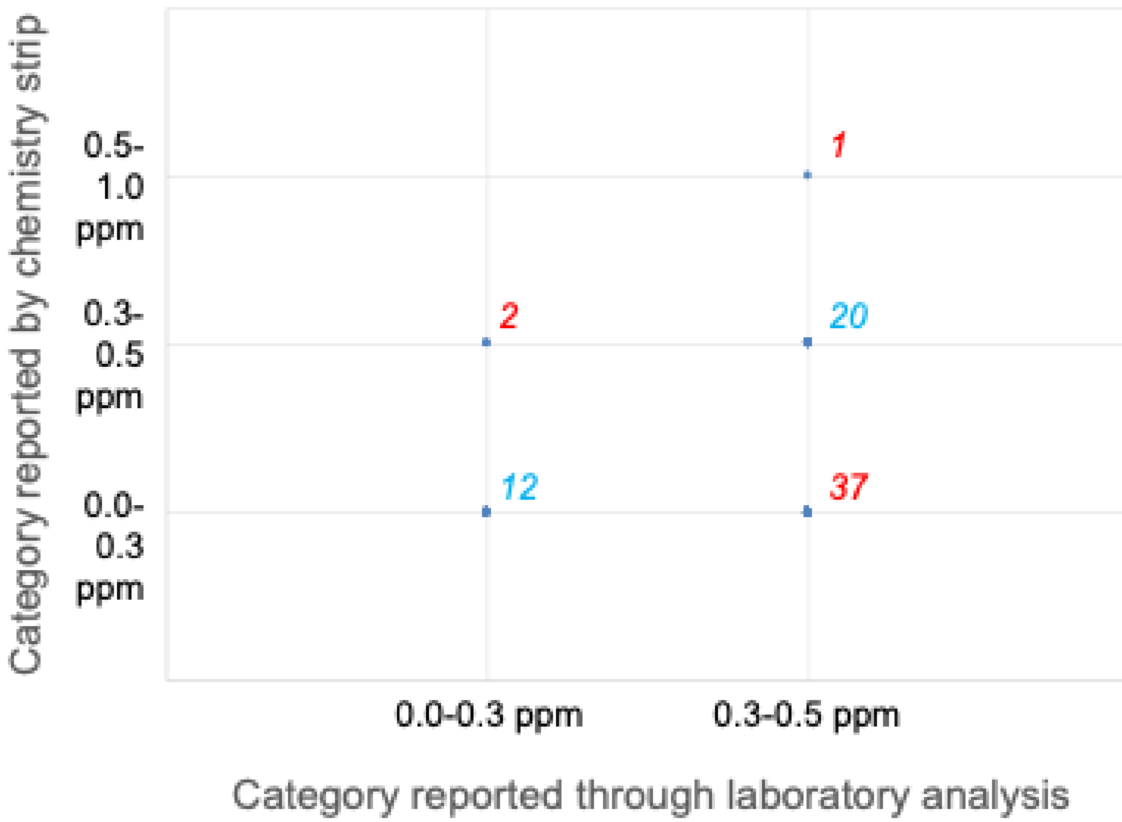

Figure 7. Scatterplot shows accuracy of chemistry strip for iron (Fe), compared with laboratory analysis. Labels indicate number of samples represented at each point; red numbers are inaccurate chemistry strip samples; blue numbers are accurate chemistry strip samples.

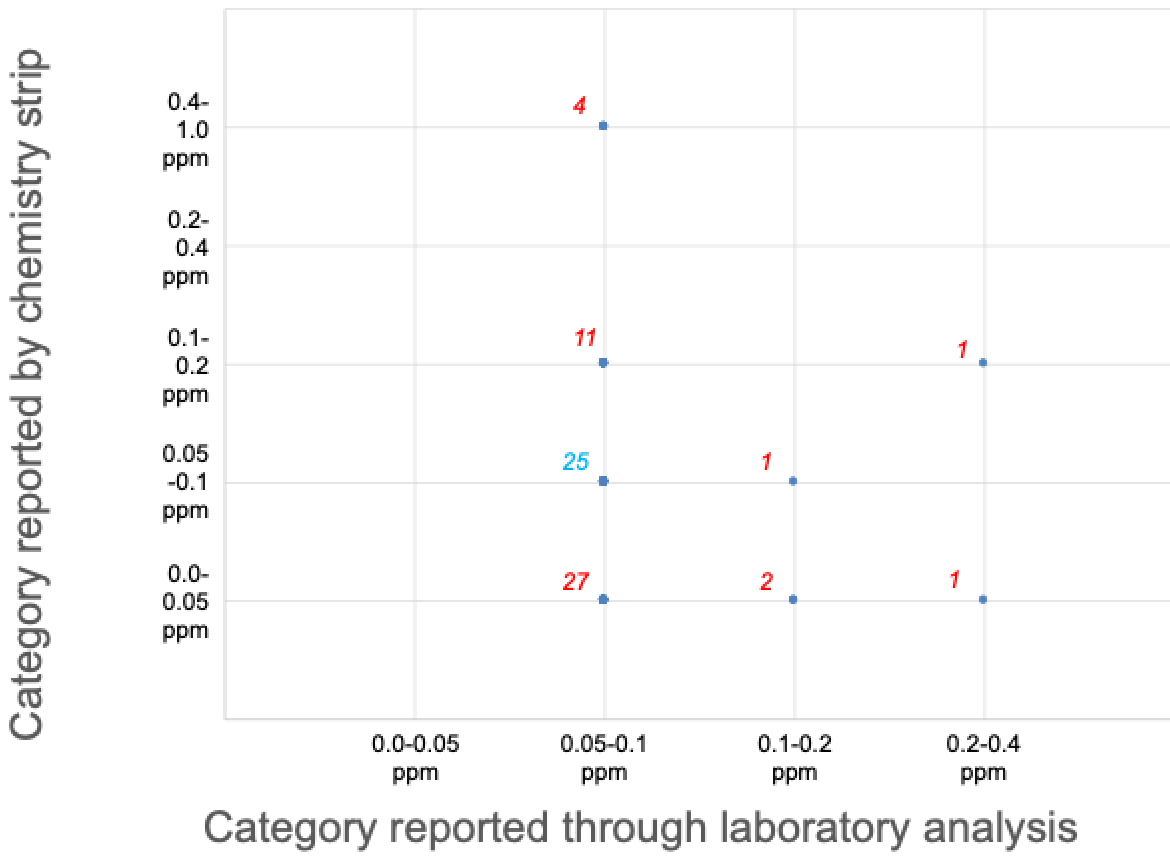

Figure 8. Scatterplot shows accuracy of chemistry strip for copper (Cu), compared with laboratory analysis. Labels indicate number of samples represented at each point; red numbers are inaccurate chemistry strip samples; blue numbers are accurate chemistry strip samples.

BBN models were developed in previous research to predict lead based on water quality parameters. The BBN was developed to use water quality parameters that were reported by chemistry strips, among other observed parameters, as input to predict lead. Eight of 72 samples report lead levels above 1.0 ppb. Preliminary research has tested a BBN model, shown in Figure 9, to predict lead for the set of 72 samples. The BBN shown in Figure 9 includes county information for samples collected in Virginia; in this application, county information was not included as an input variable. The BBN has not been able to accurately characterize the samples that contain lead, and further research is exploring which input variables should be included to improve the performance of the model.

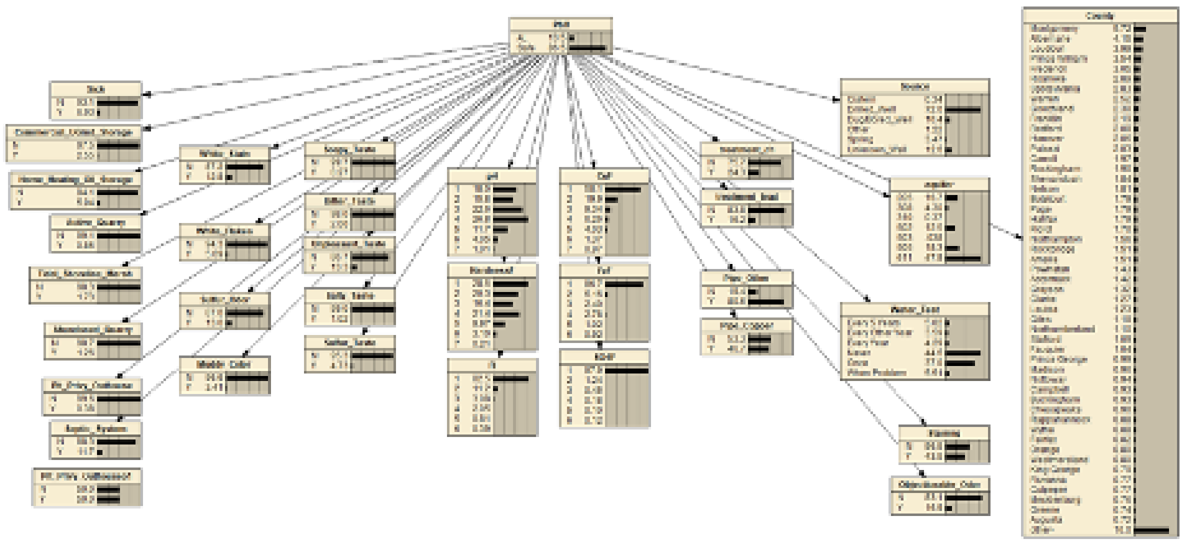

Figure 9. BBN model that was developed in previously conducted research to classify lead (PbX in the figure) as exceeding a threshold. Input parameters include six water quality parameters reported by an at-home water quality test kit: pH, copper (CuF), hardness (HardnessF), iron (FeF), fluoride (Fl), and sulfate (SO4F).

6. Discussion

The “A Citizen Science Internship Program to Quantify Racial and Economic Disparities in Lead Levels in Drinking Water Across North Carolina” award from the North Carolina Water Resources Research Institute has four primary objectives to 1) document lead plumbing and contamination across the state of North Carolina, 2) provide research internships for underrepresented students at HBCUs, 3) to increase awareness and self-efficacy related to addressing lead contamination in household drinking water, especially within diverse communities, and 4) to refine a BBN model for predicting lead levels in household drinking water based on citizen science data from Crowd the Tap. Over the course of the first year of this grant, we have made progress towards each of these objectives.

Through the Crowd the Tap citizen science project, we have crowdsourced the locations of plumbing materials and leaded water across 81 of North Carolina’s 100 counties. Households provided data on 1989 in-home plumbing pipe materials, 32 (1.6%) of which were lead baring, and 1671 service line or well casing pipe materials, 20 (1.2%) of which were lead baring. The plumbing materials identified align roughly with estimates from the National Resource Defense Council that 1.9% of United States homes are served by lead baring plumbing (2021). When comparing at-home lead test results and lead levels from laboratory ICP-MS analysis, there was a high incidence of false negatives and lower incidence of false positives with a 15 ppb threshold. While more data is needed to validate the efficacy of at-home lead tests to accurately depict lead levels, our preliminary results from people's households seem to counter laboratory assessments of the at-home lead test (Kriss et al. 2021). There were approximately equal proportions of false negatives and false positives for screenings.

We have also provided 43 undergraduate students and post baccalaureates with research internships through Crowd the Tap that have reached hundreds of households through various facilitator organizations. 13 of these interns attend HBCUs (12 from Shaw University and one from North Carolina Agricultural and Technical University), and 16 are underrepresented in science and engineering. Undergraduate research opportunities are a common predictor of persistence into science and engineering graduate programs (Kyoung Ro, Lattuca and Alcott 2017; Sell, Naginey and Stanton 2018). Previous research suggests that these experiences are particularly important for Black and African American students who may be less likely to pursue undergraduate research opportunities (Hurtado et al. 2008). Since HBCUs have been crucial for supporting Black and African American students' success in science and engineering (NCSES 2021), research internships like the Crowd the Tap internship that are run out of HBCUs may be crucial to encouraging persistence on to graduate school of Black and African American students in science and engineering fields.

Our third objective was to engage diverse communities across the state in Crowd the Tap. Many citizen science projects like Crowd the Tap struggle to engage diverse participants (Allf et al. 2022; NASEM 2018; Pateman, Dyke and West 2021) which hinders them from supporting low income and communities of color from obtaining the data they need to advocate for themselves (Blake, Rhanor and Pajic 2020; Mahmoudi et al. 2022). This is especially problematic in a project like Crowd the Tap that addresses lead contamination in household drinking water, an issue known to more disproportionately affect communities that are lower income and have a high proportion of people of color (Benfer 2017; Muller, Sampson and Winter 2018; Sadler, LaChance and Hanna-Attisha 2017).

Our assessment of nationwide Crowd the Tap participants suggest that with the exception of Hispanic and Latino participants, our results were on par with the national average. That said, 41% of multiracial households identified as White and Hispanic or Latino. Given that we measured race and ethnicity together, it is possible that more people may have selected White and Hispanic or Latino to represent their race as White and their ethnicity as Hispanic or Latino, when others may have just selected Hispanic or Latino. While our data suggest that we reached more diverse communities than most citizen science efforts, for the sake of equity, we should have over-sampled communities of color. To address this limitation we have continued to target our sampling efforts towards these communities including reaching out to teachers in these areas, helping with a North Carolina Environmental Justice Network outreach event in the city of Rocky Mount, and partnering with a community-based health organization that serves a primarily Black community.

Finally, we are refining a BBN model for predicting lead levels in drinking water using data collected by citizen scientists through Crowd the Tap. The model was originally developed using data from water samples from the Virginia Household Water Quality Program run at Virginia Tech (Fasaee et al. 2021, 2022). Preliminary results suggest that there are errors associated with the water chemistry test strips used in the screening process, and that the BBN model has low predictive performance for predicting lead levels in household drinking water. The inaccuracy of chemistry test strips is unsurprising given previous research suggested that portable, colorimetric measures of lead are inaccurate even with acidification, but especially without it (Doré et al. 2020). We are continuing in follow-up research to test new approaches to improve the performance of the BBN model to improve predictability of the water chemistry test strips by characterizing error in reading chemistry test strips by home-owners and including additional parameters as input to the BBN model. These research directions will be explored in future efforts.

7. Summary

Through the “A Citizen Science Internship Program to Quantify Racial and Economic Disparities in Lead Levels in Drinking Water Across North Carolina” Grant (# 21-17-W) from the North Carolina Water Resources Research Institute, we set out to achieve four objectives. The first objective is to characterize lead plumbing in North Carolina. Since Crowd the Tap was started until August 8, 2023, 1796 North Carolina residents have screened their home through Crowd the Tap, identifying 1989 in-home plumbing materials and 1671 service line or well casing materials, of which 32 in-home pipes and 20 service lines or well casings were leaded. We have also tested 365 North Carolina households’ water and conducted at-home lead tests on the water in 208 North Carolina households. The second objective was to provided mentored research experiences to undergraduate students, and especially those at HBCUs. We have supported 43 undergraduate and post-baccalaureate researchers, 13 of whom attend HBCUs. Altogether 16 interns have underrepresented identities and another six are people of color. The third objective was to engage diverse communities. While we may not have over-sampled from diverse communities as would be equitable in a project on lead contamination in drinking water, our sampling efforts are similar to the racial and ethnic breakdown of the United States population generally. Our final objective was to refine a statistical model to estimate water lead levels using citizen science data. We tested the BBN modeling approach using Crowd the Tap data, and this analysis demonstrated that the BBN did not improve the predictability of water lead levels in tap water. Based on the analysis that was completed, we have identified further research that is needed to refine the BBN approach and improve the predictive performance. Thus, Crowd the Tap has achieved each of these objectives.

8. Conclusions

8.1. Objective 1: Crowdsource Leading Plumbing and Risk

- 1796 North Carolina households were recruited to screen between the start of the project and August 8, 2023. 32 North Carolina households had leaded in-home plumbing and 20 with leaded service lines or well casings.
- Households were recruited to screen in 81 of North Carolina's 100 counties.
- 365 North Carolina households tested water in the lab through ICP-MS. 299 North Carolina households had at least some detectable lead and seven had lead levels greater than 10 ppb.
- 208 North Carolina households conducted at-home lead tests, and nine were positive for lead.

8.2. Objective 2: Provide Internships for Underrepresented Students

- 43 undergraduate and post-baccalaureate interns have worked on Crowd the Tap.
- 13 of these undergraduate students attend HBCUs.
- 16 are underrepresented in science and engineering.
- 22 identify as people of color.

8.3. Objective 3: Increasing Awareness and Self-Efficacy for Related to Drinking Water, Especially for Diverse Communities

- Recruitment through facilitator organizations like high school and university classrooms, corporate volunteer programs, and faith communities increased the diversity of households recruited to Crowd the Tap.
- K16 schools and faith communities were especially important for recruiting Black and African American households. K12 schools were important for recruiting Hispanic Households.

8.4. Objective 4: Refining a BBN Model for Predicting Lead Based on Citizen Science Data

- Preliminary results suggest that at-home chemistry test strips are inaccurate.
- Preliminary results suggest that the BBN model has low predictive ability to predict lead levels in household drinking water.

9. Recommendations

9.1. Objective 1: Crowdsource Leading Plumbing and Risk

- Utility companies can use zip code level data on the locations of lead piping and leaded water to prioritize locations to inventory for Lead and Copper Rule Revision regulations.
- Policymakers and government agencies can use zip code level data to inform efforts to distribute funds for leaded infrastructure remediation.

- Activist groups can use zip code level data to inform advocacy efforts for distribution of funds and other resources to support leaded infrastructure remediation efforts.
- Households wanting more affordable means of assessing risk of lead may be able to conduct at-home lead tests. If their results are negative, it is likely that their water contains less than 15 ppb of lead. That said, lead levels below 15 ppb may still be harmful to human health.

9.2. Objective 2: Provide Internships for Underrepresented Students

- Our internship programs have been most successful (in terms of the number of households screened, lemon tests conducted, and water samples tested) when students engage their own communities in the project or partner with a community that has a high level of buy-in and capacity to participate.

9.3. Objective 3: Increasing Awareness and Self-Efficacy for Related to Drinking Water, Especially for Diverse Communities

- Engaging participants through high school and college classrooms and faith communities may help increase participant diversity in a citizen science project.
- Engaging classes that serve a larger proportion of people of color, either through K12 schools or minority serving institutions, may also help increase participant diversity.
- Engaging participants through corporate volunteer programs may help increase recruitment, but may not help increase diversity.

9.4. Objective 4: Refining a BBN Model for Predicting Lead Based on Citizen Science Data

- Future screening efforts may consider excluding the use of water chemistry test strips given their inaccuracy.

10. References

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11. Appendix 1

Abbreviation	Definition
BBN	Bayesian Belief Network
DAG	Directed Acyclic Graph
HBCU	Historically Black College or University
ICP-MS	Inductively coupled plasma mass spectroscopy
NCSU	North Carolina State University
PPM	Parts per million
WRRI	Water Resources Research Institute

12. Appendix 2

12.1. Publications

- Fasaee, M.A.K., Pesantez, J., Pieper, K., Ling, E., Benham, B., Edwards, M., and Berglund, E.Z. (2022). Developing Early Warning Systems to Predict Water Lead Levels in Tap Water for Private Systems. *Water Research*, 221, 118787.
- Fasaee, M.A.K., E. Berglund, K. Pieper, E. Ling, B. Benham, M. Edwards. (2021). Developing a Framework for Classifying Water Lead Levels at Private Drinking Water Systems: A Bayesian Belief Network Approach. *Water Research*, 189(1), 116641, doi: 10.1016/j.watres.2020.116641.
- Lin Hunter, D. E., V. A. Johnson, C. B. Cooper. Diversifying large-scale participatory science: A case study of the efficacy of recruiting through facilitator organizations. In press: *Citizen Science Theory and Practice*.
- Lin Hunter, D. E., C. B. Cooper. The dual nature of trust in participatory science projects: An investigation into data quality and participant privacy preferences. In prep: *Citizen Science Theory and Practice*.
- Katner A, Irving J, Gilliland A, Cooper C, Edwards M, Jones J, Subra W, Berglund E, Pieper K. Will a shared responsibility approach to water management work? Challenges, change catalysts, and citizen-centric approaches to accessing clean drinking water. In prep.
- Katner A, Irving J, Gilliland A, Cooper C, Edwards M, Jones J, Subra W, Orr M, Berglund E, Pieper K. Wicked water challenges, change catalysts, and citizen-centric approaches to water system support, oversight and enforcement, and autonomous household water treatment and testing. In prep.

- Fasaee MAK, Dasanayaka A, Vizanko B, Armstrong K, Cooper C, Pieper K, Ling E, Benham B, Edwards MA, Berglund E. Classifying Lead Levels in Tap Water using Public Science Data and Bayesian Belief Network Models. In prep.
- A paper summarizing screening data
- A paper summarizing lab data + survey results on trust in drinking water

12.2. Presentations

- Holdsclaw, S.* D. E. Lin Hunter, C. B. Cooper. (2023, July). The Impact of Water Sources on Lead Contamination in Drinking Water. Poster. Undergraduate Research Symposium, North Carolina State University. Raleigh, NC. *Undergraduate research mentee.
- Pene, M.,* M. Strocchi,* D. E. Lin Hunter, V. Bitting, V. A. Johnson, C. B. Cooper. (2023, July). The Impact of Water Sources on Lead Contamination in Drinking Water. Poster. Undergraduate Research Symposium, North Carolina State University. Raleigh, NC. *Undergraduate research mentee.
- Berglund, E. Z., M. A. K. Fasaee, D. E. Lin Hunter, C. B. Cooper. (2023, May) Collecting at-home water quality observations through a citizen science project to characterize risk of lead in drinking water. World Environmental & Water Resources Congress 2023, Henderson, NV. DOI: https://doi.org/10.1061/9780784484852.051.
- Lin Hunter, D. E., J. Parish, C. Hawn, G. L. Jenni, & C. B. Cooper. (2023, May). Inclusion, Equity, and Accessibility in Large-scale Projects: Successes, failures, and not-yets. C*Sci 2023. Phoenix, AZ.
- Smith, H. E., D. E. Lin Hunter, & B. Allf. (2023, May). Exploring the Roles of Facilitator Organizations in Citizen and Community Science. C*Sci 2023. Phoenix, AZ.
- Lin Hunter, D. E. & C. B. Cooper. (2023, May). Diversifying large-scale project participants by recruiting through facilitator organizations. C*Sci 2023. Phoenix, AZ.
- Holdsclaw, S.*, T. Phelps*, D. E. Lin Hunter, C. B. Cooper. (2023, April). Lead Contamination Risk Across Regions of North Carolina. Poster. Undergraduate Research Symposium, North Carolina State University. Raleigh, NC. *Undergraduate research mentee
- Poteat, D.*, A. Sen*, S. Chamberlain*, D. E. Lin Hunter, C. B. Cooper. (2023, April). Relationship Between Household Location and Risk of Lead Contamination in North Carolina. Poster. Undergraduate Research Symposium, North Carolina State University. Raleigh, NC. *Undergraduate research mentee
- Lin Hunter, D. E., C. B. Cooper. (2023, April). Take a Step Towards Safe Drinking Water with Crowd the Tap. SciStarter Citizen Science Month Webinar.

- Copper, C. B., & D. E. Lin Hunter. (2023, April). Crowd the Tap: How to identify lead contamination in drinking water. North Carolina Environmental Justice Network Civic Engagement Series.
- Copper, C. B., & D. E. Lin Hunter. (2023, March). Engaging Diverse Participants in Screening Drinking Water Quality via a Variety of Facilitator Organizations. Consortium of Universities for the Advancement of Hydrologic Science. Virtual.
- Lin Hunter, D. E. (2023, February). Crowd the Tap Teacher Training.
- Lin Hunter, D. E. & C. B. Cooper. (2022, December). Crowd the Tap: A Participatory Science Initiative to Identify and Address Lead Contamination in Tap Water. Oral Presentation. American Geophysical Union 2022 Fall Meeting. Chicago, IL.
- Lin Hunter, D. E. & C. B. Cooper. (2022, December). Crowd the Tap: A novel solution to meeting the Environmental Protection Agency's Revised Lead and Copper Rule Regulations. North Carolina Water Operators Association.
- Lin Hunter, D. E. (2022, November). Crowd the Tap: Everyday access to safe drinking water. Guest lecture at North Carolina State University Instructional Materials in Science class.
- Lin Hunter, D. E. (2022, October). Crowd the Tap Teacher Training.
- Lin Hunter, D. E. (2022, September). North Carolina Water Operators Association Fall School Exhibitor.
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- Fasaee, M.A.K., Pesantez, J.E., Berglund, E.Z. (2020). "Lead Contamination Risk in Wells with Citizen Science and Modeling." EWRI Emerging and Innovative Technologies Committee Tech Talks Seminar Series, https://www.youtube.com/watch?v=648V5O5COF4
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