Protection Through Participation: Crowdsourced Tap Water Quality Monitoring for Enhanced Public Health

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Abstract

Lead contamination in municipal drinking water is a national public health issue and is generally the result of water contact with leaded distribution piping and on premise plumbing. As a result, the US Environmental Protection Agency's Lead and Copper Rule requires point of use sampling methods at a small fraction of consumer taps on the public water distribution system. While this approach is practical, it leaves large gaps of consumers without direct monitoring and protection. In response, a novel contest-based crowdsourcing study was conducted to engage the public in monitoring their own water quality at their home taps and study factors that shaped participation in drinking water monitoring. Participants were asked to collect samples of their household drinking water through social media postings, kiosks, and community events with the chance to win a cash prize. The project distributed approximately 800 sampling packets and received 147 packets from participants of which 93% had at least partially completed surveys. On average, private wells were found to have higher lead levels than the public water supply, and the higher lead levels were not attributed to older building age. There is also no statistical relevance between the participants’ perceived and actual tap water quality. Survey responses indicated that citizens were motivated to participate in the project due to concerns about their own health and/or the health of their families. In contrast, participants reported that they were not motivated by the cash prize. This project helps inform future public engagement with water quality monitoring, create new knowledge about the influence of personal motivations for participation, and provide recommendations to help increase awareness of water quality issues.

Keywords

Citizen science/crowdsourcing; Lead and Copper Rule; lead in consumer taps; drinking water quality monitoring; public supply and private wells; participation motivations

1. Introduction

Improvements in drinking water technology have contributed greatly to public health protection in the last century (Cutler and Miller 2005). However, lead is still a recurring and pervasive problem for residents across the United States (US). A survey conducted by the American Water Works Association in 2016 estimated that there are 6.1 million lead service lines (either full or partial) which serve 15 to 22 million people (Cornwell et al. 2016). Homeowners who do not have lead pipes but have lead solder and/or brass fittings in the premise plumbing are also susceptible to lead contamination by corrosion (NRC 2006). Lead consumption through drinking water is estimated to account for more than 20% of American's total lead exposure (USEPA 2018a). This percentage can increase to 85% or more of total exposure for infants who consume mostly formula made with tap water (Roy and Edwards 2018, USEPA 2018a). Lead can have damaging effects on the cardiovascular, nervous, and hematopoietic systems, especially the developing nerve systems of young children, infants, and fetuses (Eubig et al. 2010, Kim et al. 2015, WHO 2018). The amount and rate of lead release is affected by a variety of factors, including stagnation time, flow rate, scale composition, system configuration, and water quality (Doré et al. 2019, Roy and Edwards 2018, Schock 1990). For example, the water crisis in Flint, MI occurred after the city switched its drinking water source to the Flint River without implementing corrosion controls which resulted in accelerated leaching and dangerously high lead levels (Pieper et al. 2017). The crisis affected approximately 100,000 residents and its repair is estimated to cost US$1.5 billion (Craft-Blacksheare 2017, Gostin 2016, Ruble et al. 2018). Unfortunately Flint, MI is not alone in its struggles, as pollution and aged infrastructure create disparate impacts for vulnerable populations across the US (Bullard 2008, Campbell et al. 2016).

Realization of the severe health implications of lead consumption pushed the US Congress to amend the Safe Drinking Water Act in 1986, which prohibited the use of leaded pipes, solder, and flux in public water systems (USEPA 1989). In 1991, the Lead and Copper Rule (LCR) was established to address lead issues in US public drinking water systems. The LCR controls lead and copper in drinking water by establishing treatment techniques and requiring systems to regularly monitor drinking water at consumer taps. The LCR set an Action Level for lead of 15 ppb, or 0.015 μg/L. If more than 10% of taps selected for monitoring (usually based on a tiered system prioritizing locations with the highest risk of lead contamination) exceed this Action Level, the municipality is required to take additional corrosion control measures as well as recommend precautionary steps to the public. While the Action Level serves as a practical guide for management actions, there is no known safe level of lead exposure (CFR 2018, USEPA 2018b, WHO 2018). Furthermore, more than 13 million US households relying on private wells are not subject to the LCR and hence have less access and protection from established services (Liu et al. 2005, NRC 2006, Pieper et al. 2015a, USEPA 2018c). The LCR is also limited in the high labor and time cost related to its execution and the difficulty in gaining access to private properties at desired times. As a result, sampling is generally conducted for less than 0.1% of the end users serviced and oftentimes, the same tap locations are monitored for each sampling period (AWWARF 2008, NRC 2006, Zhang et al. 2009). Because of these limitations, the Environmental Protection Agency (EPA) is looking to improve the LCR with the goal of minimizing lead exposure, designing clearer and more enforceable requirements, creating stronger consumer education programs, addressing environmental justice, and integrating drinking water with cross-media lead reduction efforts (USEPA 2016). Achieving this goal requires looking beyond the traditional monitoring and data collection strategies.

Over the last two decades, a rapidly growing body of research has demonstrated that crowdsourcing and engaging members of the public in environmental monitoring can increase capacities to address complex problems like the public health crisis from drinking water contamination (Bonney et al. 2014, Conrad and Hilchey 2011, Fox et al. 2016). Crowdsourcing has traditionally been used as a low-cost solution to large-scale tasks that can be addressed by widely distributed and independent citizens(Howe 2006, Jeppesen and Lakhani 2010, Malone et al. 2010). When applied to water quality monitoring, a crowdsourcing scheme is able to utilize the resources and knowledge of citizens to substantially reduce the cost, time, and professional labor needed for sample collection and/or analysis, increase the efficiency of individual monitoring activities, and help better allocate limited public resources (Bonney et al. 2009, Silvertown 2009). Previous projects that utilize citizen science in environmental monitoring are often focused on natural resources and ecosystem services such as wildlife, water resources, soil, and plants rather than engineered systems (Bonney et al. 2009, Bonney et al. 2014, Conrad and Hilchey 2011, Dickinson et al. 2012, Jollymore et al. 2017, Pandya 2012, Shirk et al. 2012, Silvertown 2009, Wiggins and Crowston 2011). Examples of the few efforts which have examined citizen science in the context of public drinking water monitoring include recent studies that involved collaborations between citizens and researchers to understand the severity of the Flint water crisis (Goovaerts 2019, Roy and Edwards 2019). A few studies have taken an empirical approach to studying social outcomes of citizen science, such as motivations, perceptions, and behaviors (Boakes et al. 2016, Raddick et al. 2009, Seymour and Haklay 2017). However, these studies have not focused on the area of public drinking water monitoring. Furthermore, understanding and strengthening/maintaining participation in crowdsourcing projects remains a key challenge. In the business realm, contest-based crowdsourcing is increasingly used to solicit innovative solutions related to computer programming, process/graphic design, pharmaceutical development, etc. (Boudreau and Lakhani 2013, Lakhani 2016, Riedl et al. 2016). Contests are often shown to be an effective way in attracting a broader audience and generating more desirable solutions (King and Lakhani 2013, Lakhani et al. 2013). Furthermore, latest findings from crowdsourcing researchers indicate that crowds, after being solicited through contests, are more likely to self-organize into a larger number of teams that could function more effectively than artificially matched teams (Blasco et al. 2013). The effect of contests in crowdsourced water quality monitoring, however, remain unknown.

In this study, we designed an innovative city-scale contest-based crowdsourced water quality monitoring scheme at the consumer tap to address some of the aforementioned limitations related to the current LCR, and investigated its effectiveness. By applying the crowdsourcing scheme, we engaged citizens to collect their own tap water samples through contests and we then tested lead concentration in these samples and conducted analyses to better understand the intersections of participation, program design, and social-environmental outcomes.

2. Methodology

2.1 Project Design

This study was carried out in a New Hampshire city which in 2017 had a population of around 30,797 people and 12,953 households (USCB 2018b). The city was selected based upon its diverse water source (65% public, 35% private) and the strong support of the local water utility on this project.

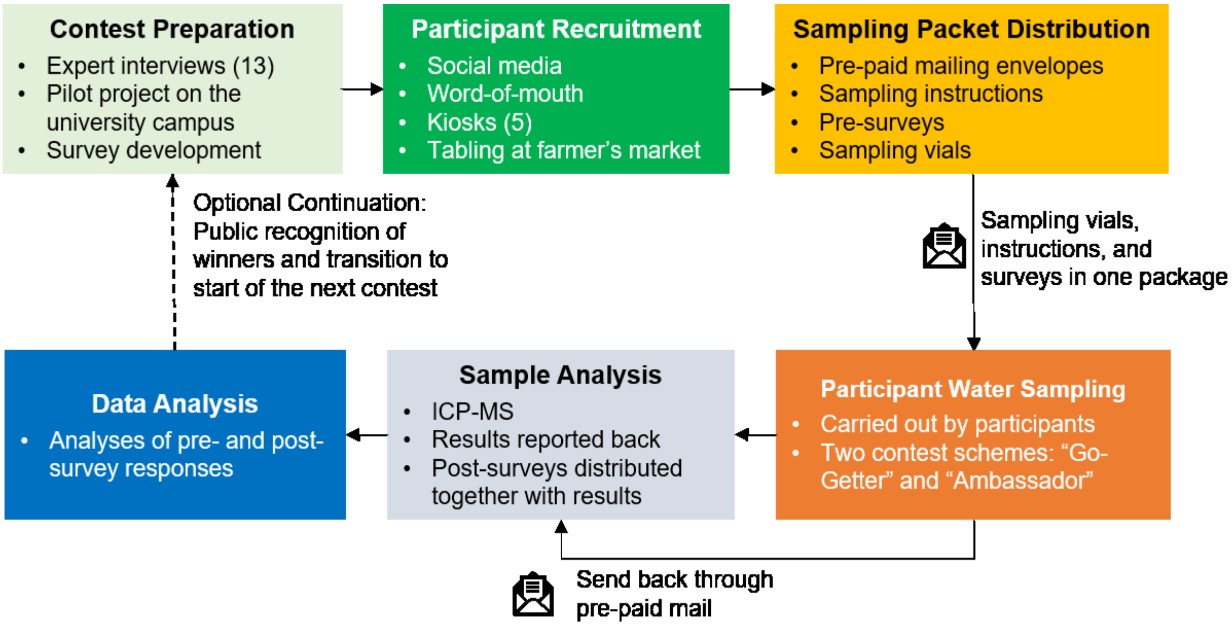

Figure 1 Process flow schematic of the tested sample collection scheme in the current project.

A schematic of the overall project design is provided in Figure 1. A total of 13 expert interviews (with regulators, utility operators, public health experts, etc.) and a pilot project on the University of New Hampshire (UNH) campus were conducted prior to the start of the project for preparation and testing purposes. Suggestions provided by the experts and lessons learned from the pilot project were used to inform the design of the current project. Participant recruitment initiated on August 5, 2018. We applied four different recruitment strategies, including: informational kiosks, social media, word of mouth, and direct interaction at a public event. Five information kiosks (Figure 2(a)), containing sampling packets, were distributed across the city at highly trafficked locations including two local grocery stores, a shopping mall, a community center, and a public library. The kiosks allowed people to take and return sampling packets directly. Facebook was selected as our social media platform based upon the presence of existing groups focused on local issues. We created a dedicated page about the project and launched a campaign specifically targeting residents of the area. During the participant recruitment stage, the page was updated weekly with the latest news about the project. A local Facebook group was also approached and utilized to promulgate the project to approximately 940 of their followers. Word of mouth recruitment approaches were conducted through developing relationships with a local church, with 700 parishioners. Church leadership informed members at weekly mass who distributed and collected samples directly. Lastly, the project team tabled at the local farmer's market on one occasion to evaluate direct interaction with the public. The official sample collection period ended on August 31, 2018. Late samples were accepted through mid-November.

Figure 2 (a) Two-level, cardboard informational kiosks were designed to attract the attention of passersby and provide key information to participate in the project. (b) Sampling packets were housed in pre-paid mailing envelopes to allow for easy return upon completion. (c) Returned samples were analyzed for lead

concentration using an inductively coupled plasma mass spectrometer at a University of New Hampshire lab.

Each recruited participant received a sampling packet that contained a pre-survey that requested sampling locations, contact information and social data related to participant perceptions and participation in the project. The packets also included an empty 50-mL sampling vial and instructions on collecting first draw samples without contaminating the sample (Figure S1 of the supporting information). Sample vials were screw top, wide mouth, and fit easily under most kitchen faucets. Participants returned the water sample either via pre-paid mail service or returning it to the sampling/informational kiosks. Upon receipt, triple distilled 70% ultra-high purity nitric acid (400µL) was added directly to the collected samples, for preservation, and samples were stored at 4°C until the time of analysis. Analyses were conducted over two efforts, the first in September 2018 and the second in November 2018, as sample packet were received. Analytical analysis was conducted at the UNH Plasma Geochemistry Lab via inductively coupled plasma mass spectrometer (ICP-MS) in accordance with EPA 200.8 (Brockhoff et al. 1999). External calibration curves using a certified standard (SPEX CertiPrep, Metuchen, NJ) were conducted at the start and conclusion of each run, along with constant calibration verification standards and blanks every 10 samples.

All water quality results were reported to project participants by the end of November 2018 primarily through individual email communications or US mail (when no email was provided). Correspondence included the concentration of lead in their water sample, guidance on interpretation and potential protective action that should be taken base upon their results, and a post-survey. All lead levels less than 1 µg/L were reported as "< 1 µg/L". Protective guidance suggestions were broken into four lead concentration brackets, "<1 µg/L," "1-5 µg/L," "5-15 µg/L," and ">15 µg/L," following resources provided by the New Hampshire Department of Environmental Services (NHDES) resources (NHDES

2016). Retesting was offered for participants who had elevated lead levels (>15 μg/L). Participants were encouraged to contact research staff with questions or concerns regarding their results.

Our social science survey design was informed by the Tailored Design Method (TDM) (Dillman et al. 2014). We used a pre- and post-survey design to describe patterns and identify outcomes from participation in the project. Both the pre- and post-survey were also administered using Qualtrics®. The surveys asked questions about participants' socio-economic characteristics, water quality perception, how participants found out about the project, motivations to participate, intended actions related to water quality information, among others. We also built from the Developing, Validating, and Implementing Situated Evaluation Instruments (DEVISE) Framework using an adapted scales for motivations to participate in crowdsourcing (Philips et al. 2017) and for environmental action (Porticella et al. 2017). To test the role of monetary incentives in motivating the public in tap water quality monitoring, two contest schemes were designed and implemented, namely "Go-Getter" and "Ambassador," each with $200 cash rewards. The "Go-Getter" scheme rewards the participant who collected the most samples from different locations. The "Ambassador" scheme rewards the participant who introduced the highest number of new recruits to the program.

2.2 Data Treatment and Analysis

The project received a total of 149 returned packets either via mail or kiosk drop-off. Two of these packets did not contain a sample. Four additional packets did not include any form of contact information. Hence, a total of 142 packets were analyzed for lead concentrations. For participants who were offered retests, the average of their original and retested sample concentrations was used in the data analysis. A total of 136 pre-survey responses and 42 post-survey responses had more than 50% questions answered, and hence were included in the survey analyses. Out of these responses, 36 pre- and post-surveys were matched for comparison. Survey responses were analyzed using IBM SPSS Version 25. We conducted descriptive and bi-variate statistical tests (t-test and chi-square) to describe patterns of participation, perceptions about water quality, and associations between independent variables. We ran a Principal Components Analysis (PCA) with a Varimax rotation to assess the underlying factors that shaped participant motivations and tested the internal reliability of this scale using Cronbach's alpha. PCA is a method used to transform a large number of related variables into a smaller number of uncorrelated variables using linear combinations, creating a simpler basis to describe the data (Everitt and Hothorn 2011, Jackson 2005).

We also used the georeferencing technique in ArcMap® to plot sampled locations in this project and compared against the current LCR sampling sites provided by the NHDES based upon their physical addresses (GRANIT; 2019, NHDES 2018). Standard deviation ellipses were then constructed, which contain two standard deviations of locations for each of the LCR and sampled datasets. The ellipses were then used to compare the area coverages of the two datasets.

3. Results and Discussions

3.1 Program Efficacy

The return rate of this project was around 18% (142 analyzed samples out of 800 distributed packets). The sample collection period lasted for a total of 26 days, and the entire project lasted for around 58 days. Figure 3 shows the location of samples collected through this project as well as the samples collected under the latest LCR sampling protocol. This study was able to almost double the number of households tested as compared to the current LCR protocol (77 households). The area covered through this project was around 140.4 km^2 based upon the standard deviation ellipse, which was around 2.3 times of the area covered by the LCR protocol (65.5 km^2). The samples collected through this project were well spread throughout the testbed city. This project has also effectively extended lead monitoring to households relying on private wells. Of the returned samples, around 67% were from families connected with the public drinking water supply and 33% were from households that rely on private wells. This was comparable to the city as a whole in which the municipality served 65% of residences (Interview 2018).

When asked if they would be willing to participate in another project like this if given the opportunity, 77% of participants who responded to this question in the post-contest survey selected "Yes" and 19% selected "Maybe." This suggested the project's potential to retain volunteers that were relatively easily accessible for future monitoring/testing activities.

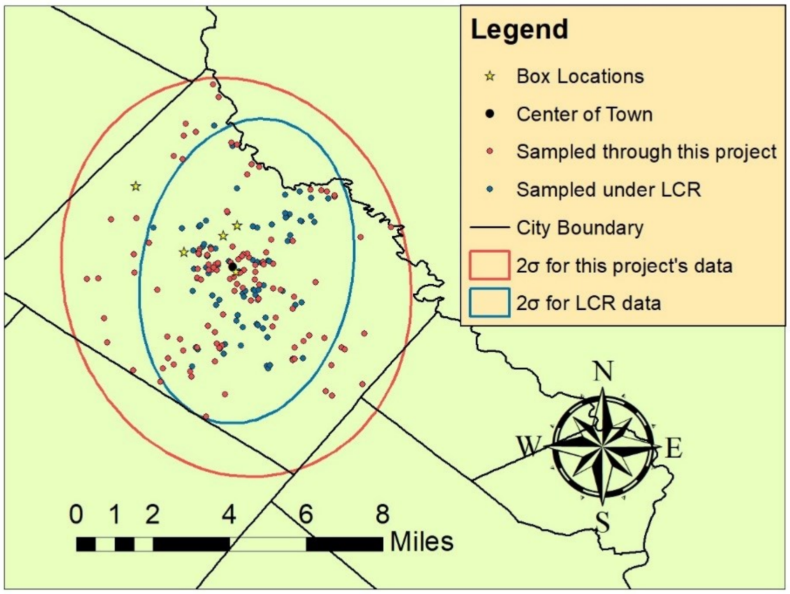

Figure 3 Map of sites in testbed city currently monitored under the LCR (blue) and sites tested during the pilot study (red). Ellipses depict statistical spread of data and contain two standard deviations (95%) of samples.

3.2 Water Sample Analysis

All samples were collected from kitchen faucets except for one sample which was taken from a garden hose and six which were taken from bathroom faucets. The majority of the samples tested (around 68%) had a lead concentration below 1 μg/L (Figure 4(a)). Around 3% of the samples tested had a higher lead concentration than the EPA action level, all of which were from private wells. An additional 7% had a lead concentration between 5 and 15 μg/L, all of which were also from private wells. About 57% of well samples had 1 μg/L or greater lead concentrations, whereas 20% of public supply samples had 1 ppb or greater. All public supply samples were below 5 μg/L, but 30% of private well samples were at or above 5 μg/L. The average lead concentration of private well samples was 7.22 μg/L with a standard deviation of 23.49 (without the retested sample, the average was 3.81 μg/L and the standard deviation was 5.52); while the average lead concentration of public supply samples was 0.613 μg/L with a standard deviation of 0.840. Lead in drinking water was often assumed to be only a problem of public supply, as attention is often centered on the failures and preventive management of large pipeline networks. Nevertheless, our study shows that households that rely on private wells are not necessarily free of lead contaminations. In fact, they could be even more the case. Potential sources of lead in well water include submersible pumps with leaded-brass components, plumping components imported from outside the US where lead is not as strictly regulated, and/or older well packer elements (CDC 2018). Another potential cause for high lead levels could be the use of ion exchange devices to reduce the hardness of sourced groundwater, thus making it more corrosive (NHDES 2009, USGS 2016). Some studies, however, indicate that ion exchange softening does not affect the corrosivity of water (Sorg et al. 1998). In general, low pH water, high dissolved oxygen, high temperature, and high levels of dissolved solids increase corrosion rates (Sadiq et al. 2007).

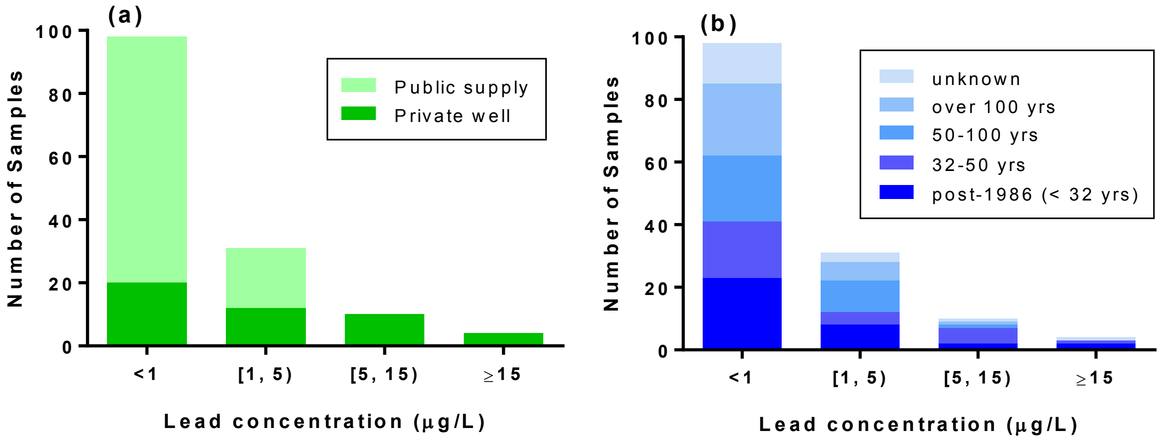

Figure 4 Distributions of (a) water sources (public vs. private) and (b) building age in relevance to their actual lead results. Remodeling was not considered in determining building age.

The higher lead concentration in private wells naturally invites the assumption that the buildings that rely on private wells might be older than the ones that rely on public supply. To obtain the age of the buildings being sampled, we searched the sampling site addresses within the city's public property assessment records database. Building ages that were not available on the database were obtained by running sampling site addresses through real estate search engines (CoStar Group 2018, NAR 2018, Zillow 2018). This analysis assumed that private wells were constructed the same year as their respective buildings. Building ages were eventually obtained for 124 samples and matched with sample analysis results obtained for the respective sample location. Figure 4(b) presents the building age in relation to their actual lead measurements. In fact, the highest lead concentrations were found in some of the newest homes in the region. Since the use of lead-containing solders in potable water systems was banned nationwide in 1986, we particularly investigated the measured lead concentrations for homes that were constructed before and after 1986. Half of the homes that were tested higher than the EPA action level were built after 1986, and one was less than 50 years old. Around 11% of the homes that were built after 1986 (less than 33 years old) have a lead concentration above 5 µg/L and around 21% of the homes that are between 32 and 50 years old have a lead concentration above 5 µg/L. However, this number is 3% for buildings between 50-100 years old and over 100 years old.

3.3 Demographics and Recruitment Patterns

Although this project aimed to encourage communication between participants, specifically with the advertisement of the "Go-Getter" and "Ambassador" contests, only 11% of participants who completed relevant survey questions indicated learning about the project via word-of-mouth and only 8% from social media. This shows the limitations of cash incentives and social media recruitment in a drinking water monitoring/testing project targeting a small, spatially constrained population. Tabling at the farmer's market also saw little success, with many citizens stating "I don't want to know" when offered free water testing. This introduces a challenging barrier of access to those who do not wish to know what is in their water. As this study did not survey those who chose not to participate, it is difficult to draw conclusions to exactly why they were deterred. These barriers would be worth investigating in future studies. Meanwhile, 53% of surveyed participants indicated they learned about the project when they saw a kiosk in person. This implies that persons of interest are more likely to participate if the project materials are directly accessible to them.

Survey results indicate that about half of the participants had an annual household income below the city's median household income (Table 1). This supports this method's ability to reach lower-income consumers, who have often been reported as socially disadvantaged groups facing inequities in water quality and are typically harder for researchers to reach due to project cost and time constraints (Bonevski et al. 2014, VanDerslice 2011). Around 26% of the participants rented their homes while 70% owned them. Persons occupying home rentals often face limited capacity in accessing resources to make changes to their homes, especially in urban areas (Mee et al. 2014). The results also show that our methods were more effective in recruiting more educated population, as the percentage of participants with a Bachelor's degree or higher was 15.5% higher than the city mean and the percentage of participants with less than high school education was 7.8% lower. This indicates education might have a positive effect on people's willingness in participating a program like this. Furthermore, we found that our project had a higher success in recruiting older citizens, with a median age of 55, which is 14 years older than the city wide median age of 41 (USCB 2018b). This is also a trend seen in other environmentally focused citizen science projects (Merenlender et al. 2016, Trumbull et al. 2000). Around 22% of the respondents had children under the age of six in their home, which was significantly higher than the national average of 11.6% households (family and non-family) with children under six in their home (USCB 2016, 2018a). This indicates that having a young child in the home could be a potential motivator for participating in this project.

Table 1. Demographic data showing gender, education levels, whether the family has children under 6 years old in the house, rent or own, and income

Characteristics	**Frequency**	**%**	**City Mean %**
Gender			
Unknown or other	7	5.2	
Male	39	28.7	48.7 (USCB 2018b)
Female	90	66.2	51.3 (USCB 2018b)
Education			
Missing	3	2.2	
Less than high school	4	2.9	10.7 (USCB 2018b)
High school graduate and/or postsecondary education	78	57.3	67.3
Bachelor’s degree or higher	51	37.5	22.0 (USCB 2018b)
Age			
Unknown	12	8.8	
18-24	1	0.7	21.0 (USCB 2018b)
25-34	21	15.4	
35-44	18	13.2	27.7 (USCB 2018b)
45-54	21	15.4	
55-64	22	16.2	12.9 (USCB 2018b)
65+	41	30.1	17.5 (USCB 2018b)
Children under 6 in the House			
Missing	6	4.4	
Yes	30	22.1	
No	100	73.5	
Rent or Own			
Unknown	5	3.7	
Rent	35	25.7	
Both	1	0.7	
Own	95	69.9	
Income			
Unknown	20	14.7	$50,759 in 2016 USD (median household income) (USCB 2018b)
$0 to $24,999	18	13.2	
$25,000 to $49,999	41	30.1	
$50,000 to $74,999	23	16.9	
$75,000 to $99,999	17	12.5	
$100,000 to $124,999	10	7.4	
$125,000 and up	7	5.1	

3.4 Lead Concentration Versus Water Quality Perception and Preventive Actions

Another question we investigated through the study was how people's perception was correlated to their actual water quality (Figure 5). Of the four participants whose lead concentrations were above the EPA action level, three of them considered their water quality to be very good or good. Around 42% of the participants with a lead concentration above 5 µg/L considered their water quality to be excellent or very good. We then recoded lead levels as a continuous data type into a binary category, where scores of ⩾ 1ug/L were recoded as 1 ("Lead") and scores <1 were recoded as 0 ("No Lead"). Similarly, we recoded water quality perceptions into binary categories, where original rankings of "Excellent", "Very good" and "Good" were recoded as 1 ("Good") and "Fair" and "Poor" as 0 ("Bad"). There was no statistically significant relationship between evidence of lead in water and perceptions about water quality (x^2=.150, df=1, p=0.699) (Table S1 in SI). This is may, in part, be due to lead in drinking water being tasteless, odorless, and colorless, and therefore undetectable to the consumer (CDC 2016). Those who ranked their drinking water as of poor quality likely did so by noticing detectable water quality issues. Lead along with some other drinking water contaminants are often not directly observable by end users, this could potentially hinder people's timely response to prevent potential harms.

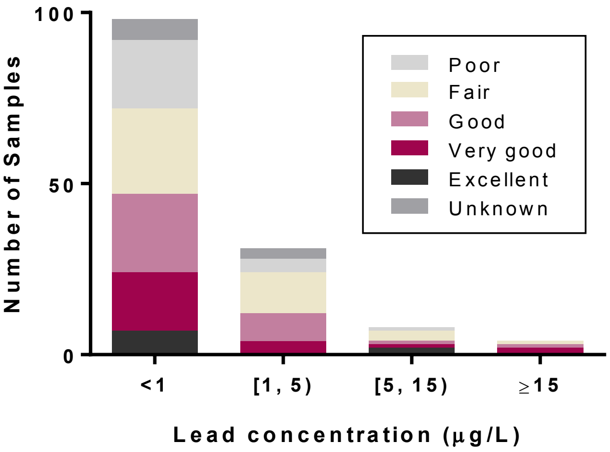

Figure 5 Correlations between lead concentration and water quality perception

We also asked participants whether or not they run their tap to flush their water before using it each day. Another chi-squared test was conducted to test the association between the respondents' water quality perceptions and actions to reduce the potential harm. Results of a Pearson Chi-Square analysis showed no statistically significant relationship between perceptions about drinking water quality (good or bad) and choice to run the tap (yes or no) in the pre-survey responses ($x^2=0.108$, df=1, p=0.743) (Table S2 in SI). This may be due to a lack of awareness of the benefits of flushing one's tap, which shows the importance of raising the public awareness of the potential drinking water issues and their preventive measures. While flushing has been widely recognized as an effective short-term method for tap water containing high lead levels, insufficient flushing time might result in increased rather than reduced lead exposure (Katner et al. 2018). Hence, it is important to provide the public with clear flushing guidelines, while acknowledging its practical limitations.

3.5 Motivation for Participation

Participation in this project was mostly motivated by wanting to learn about drinking water quality (around 94% of the participants either agreed or strongly agreed in the pre-survey) and concerns about personal health and/or family health (around 95% either agreed or strongly agreed in the pre-survey). A PCA on the pre-survey responses further identified three main motivation factors which we labelled health and identity, extrinsic incentives, and personal satisfaction (Table 2). The health and identity factor corresponded with the highest rated mean motivations, providing further evidence that health and identity related factors were key factors that motivated participation in the contest. This finding has implications for recommendations of how to design communication plans to help encourage people to participate in household drinking water monitoring activities. On the other hand, the contest and the cash prize were found to be an ineffective motivator for people to participate this project. Around 67% of participants either disagreed or strongly disagreed that they were motivated to participate by the cash prize, and 21% were neutral. Additionally, when asked which contest the participant hoped to win, 82% of participants responded "Neither" in the pre-survey (Table S3 in the SI). For those who participated and also responded to the post-survey, 92% (n=39) indicated they were not participating in either of the contest options. A paired t-test comparing responses to pre- and post-survey questions on motivation revealed no significant differences in overall motivations before and after the project (Table S4 in the SI). However, participants do show a decrease in motivation to learn about water quality. We interpreted this result to indicate that the project may have helped satisfy their motivation for learning about water quality.

Table 2. Results from Principal Components Analysis (PCA) of pre-survey data showing rotated factor loadings (Varimax rotation) on two primary motivation factors which accounted for 59% of the variance. Motivation factors included health and identity, extrinsic incentives, and personal satisfaction. The scale demonstrated internal consistency (Cronbach's Alpha = 0.747)

"I'm interested in participating in this drinking water quality contest because…"

N=136	**Extrinsic**	**Intrinsic**
Of the recognition or respect I'll get from others.	**0.836**	-0.076
People I look up to think it's good to participate in this contest.	**0.814**	0.015
I want others to think I'm good at doing activities related to environmental health.	**0.727**	0.046
I am required to participate in this contest.	**0.629**	-0.374
Participating in this contest will help me achieve things that are important to me.	**0.621**	0.257
I want to win the cash prize.	**0.621**	-0.171
I care about my family's health.	-0.154	**0.880**
I care about my personal health.	-0.190	**0.873**
I am an environmentally conscious person.	0.189	**0.747**
I want to learn about my drinking water quality.	-0.064	**0.703**
I enjoy doing activities related to environmental health.	0.491	**0.544**

4. Conclusions

This project has demonstrated that well designed crowdsourcing approaches can identify lead concentrations at the consumer tap while actively engaging and informing the public, which directly addresses a large portion of the EPA's LCR revision goals. An important finding in this study is that lead concentrations were statistically higher at locations served by private wells than the public system, and the lead concentrations are not corresponding to the age of the households. This is consistent with several studies conducted over the past 5 decades in North Carolina, Pennsylvania, and Virginia (Francis et al. 1984, Maas and Patch 1990, Pieper et al. 2015b, Swistock et al. 1993). While lead exposure has decreased in public systems, exposure from private systems remains a large data gap in lead exposure which may pose challenges in achieving the federal goal to eliminate elevated blood lead levels in children by 2020 (DHHS 2012). Perceptions of water quality was found to be neither linked with the actual lead concentration, nor the preventive actions people take to minimize harm (i.e., flush tap), indicating a potential barrier protection of public health. Our participant recruitment has a higher success with female, more educated, and older populations. Though our hands-off recruitment approach was useful in reducing time and resource requirements for researchers, it should be noted that methods such as door-to-door may be more effective in achieving higher return rates. Furthermore, personal contact with the kiosks was found to be the most effective approach to recruitment. Participants are mostly motivated by health and identity factors. These findings have implications on the future design of communication strategies to improve communication efficacy and engage the under-represented groups.

We envision the design of the crowdsourced scheme developed in this study could be expanded to other contaminants of concern. Outcomes from this project have demonstrated the effectiveness of such a scheme in terms of the amount of households sampled and the area covered. However, the usefulness and broader adoption of such a scheme in monitoring water quality also depends on the availability of easy-to-understand/use sampling and analysis methods as well as low cost contaminant analysis techniques. In our project, we utilized a different method than the standard lead testing method, because the standard method requires collection of one liter of water sample, which would have been a barrier for transporting and testing those samples in one centralized location. In our design, we were not able to allow participants to directly analyze their samples, due to the lack of low-cost but accurate lead testing techniques that can be freely distributed to the participants. A direction of potential future research is to develop such low-cost measuring techniques, sensors, or surrogate indicators for household water quality monitoring. We expect the availability of such techniques would greatly enhance our capability in providing continuous or random water quality checks for public health protection.

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Author Contributions

W.M., B.M., and S.G. conceived and designed the project. S.J., L.P., S.G., W.M., and B.M. implemented the project in the test city. S.G., S.J., L.P., and M.F. conducted the lead analyses. B.M. and S.J. conducted the survey analyses. S.J., W.M., B.M., and S.G. wrote the paper. J.B. provided ICP-MS to the team at a collaborative rate. Author list is based on role, not contribution.

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