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A Mixed Methods Approach to Understanding the Public Health Impact of a School-Based Citizen Science Program to Reduce Arsenic in Private Well Water

Ashley Taylor,[1] Alexis Garretson,[1] Karen H. Bieluch,[2] Kate L. Buckman,[3] Hannah Lust,[1] Cait Bailey,[1] Anna E. Farrell,[1] Brian P. Jackson,[2] Rebecca Lincoln,[4] Erin Arneson,[4,5] Sarah R. Hall,[6] Bruce A. Stanton,[7] and Jane E. Disney[1]

[1]MDI Biological Laboratory, Bar Harbor, Maine, USA
[2]Dartmouth College, Steele Hall, Earth Sciences, Hanover, New Hampshire, USA
[3]Connecticut River Conservancy, Greenfield, Massachusetts, USA
[4]Maine Center for Disease Control and Prevention, Augusta, Maine, USA
[5]Muskie School of Public Service, University of Southern Maine, Portland, Maine, USA
[6]College of the Atlantic, Bar Harbor, Maine, USA
[7]Geisel School of Medicine at Dartmouth, Hanover, New Hampshire, USA

BACKGROUND: Exposure to arsenic (As) in well water is a well-documented public health issue for Maine and New Hampshire, as well as for other states in the United States and abroad. Arsenic contamination of well water in these locations is primarily attributed to metasedimentary bedrock that leaches As into groundwater. However, As can also enter groundwater reserves from soils contaminated by the historical use of arsenical pesticides. Approximately half of the households in Maine and New Hampshire rely on private wells, many of which have elevated As. Arsenic exposure has been associated with an increased risk of cancer, cardiovascular disease, reduced infection resistance, and lower intelligence quotient in children. Despite these known health impacts, well water testing and treatment are not universal.

OBJECTIVES: We have approached the problem of low well water testing rates in Maine and New Hampshire communities by developing the All About Arsenic (AAA) project, which engages secondary school teachers and students as citizen scientists in collecting well water samples for analysis of As and other toxic metals and supports their outreach efforts to their communities.

METHODS: We assessed this project's public health impact by analyzing student data relative to existing well water quality datasets in both states. In addition, we surveyed private well owners who contributed well water samples to the project to determine the actions taken to mitigate As in well water.

RESULTS: Students collected 3,070 drinking water samples for metals testing, and 752 exceeded New Hampshire's As standard of 5 ppb. The AAA data has more than doubled the amount of information available to public health agencies about well water quality in multiple municipalities across both states. Students also collected information about well types and treatment systems. Their data reveal that some homeowners did not know what type of wells they had or whether they had filtration systems. Those with filtration systems were often unaware of the type of system, what the system was filtering for, or whether the system was designed to remove As. Through interviews with pilot survey participants, we learned that some had begun mitigating their exposure to As and other toxic metals in response to test results from the AAA project.

DISCUSSION: A school-based approach to collecting and analyzing private well water samples can successfully reach communities with low testing rates for toxic elements, such as As and other metals. Importantly, information generated through the program can impact household decision-making, and students can influence local and state policymaking by sharing information in their communities. https://doi.org/10.1289/EHP13421

Introduction

Arsenic (As) in well water is a well-documented public health issue around the world, including in Northern New England states. Of particular note is that bladder cancer mortality rates are ∼20% higher in Maine, New Hampshire, and Vermont than in the United States overall. This has been attributed to long-term exposure to As in well water, particularly dug wells dating from the early part of the 20th century.[1] Arsenic may contaminate dug wells in locations where arsenical pesticides, such as lead arsenate, were historically used[2] and drilled wells in areas where As-laden metasedimentary bedrock is found.[3] Water from some wells in Maine and New Hampshire far exceeds the US Environmental Protection Agency (EPA) maximum contaminant level (MCL) for public water systems of 10 ppb, with a maximum measured water concentration of 3,100 ppb reported in the Maine Tracking Network[4] and 1,040 ppb in the New Hampshire Department of Health and Human Services (DHHS) Data Portal.[5] It should be noted that MCLs only apply to public drinking water systems, not private water sources such as wells, given that these are currently not regulated in the United States. Given the potential for extremely high As levels in drinking water in Maine and New Hampshire, As presents a significant public health issue in both states. In addition to bladder cancer, there is a litany of health impacts that are associated with long-term exposure to As, including cancer of the lung, liver, prostate, and skin, as well as the potential for cardiovascular, pulmonary, immunological, neurological, reproductive, and endocrine problems.[6–10]

In studies specific to New England, exposure to As has been associated with adverse birth outcomes, such as reduced birth weight in New Hampshire[11]; a study in Maine found that As in drinking water, at levels ≥5 ppb, was negatively associated with childhood intelligence quotient (IQ) and may pose a threat to child development.[12]

Despite growing knowledge of the health impacts of As exposure, research demonstrates that people do not regularly test their well water for As, and even when they know there is As in the water, they may not treat their water to remove it.[13–18] Specifically, a study of well owners in Maine found that 41% had never tested their wells for As.[14] Numerous factors influence testing and treatment behavior, including knowledge (education, perception of risk, and personal concerns about As), resources (socioeconomic

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Address correspondence to Jane E. Disney, MDI Biological Laboratory, 159 Old Bar Harbor Rd., Bar Harbor, ME 04609 USA. Telephone: (207) 288-9880, ext. 423. Email: jdisney@mdibl.org

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status, time, and ability to test well water), and community involvement (having neighbors who regularly test their wells).[14–18]

Because unregulated private wells provide drinking water to approximately half of the homes in Maine and New Hampshire, and many residents are unaware that As is a problem, addressing the public health impacts of As in well water requires creative solutions. Citizen science programs are increasingly used to foster community engagement with pressing local challenges, including environmental health issues.[19] In a survey of citizen science practitioners across Europe, citizen science was shown to address environmental goals by generating knowledge, creating learning opportunities, and enabling civic participation.[20] Across environmental fields, student data collection and school-based programs have encouraged appreciation of environmental issues and provided a framework for teaching the scientific method.[21,22] School-based interventions have also been successfully applied in the context of drinking water contamination, such as one in Bangladesh, which prompted families to switch from high-As household wells to new low-AAs community wells.[23] In addition, school-based recruitment of residents for well water testing proved successful in two townships in New Jersey.[24] Similarly, we recognized the potential of school-based citizen science programs to address As in well water and launched a secondary school-based program called All About Arsenic (AAA) in 2016. AAA engages teachers and students as citizen scientists in collecting well water samples for As analysis with dual education and public health goals focused on addressing As and other toxic metals in private wells.[25] Figure 1 graphically represents the AAA program, which, in seeking to address health issues through data collection and sharing, has resulted in a large publicly available dataset, family and community conversations about As,

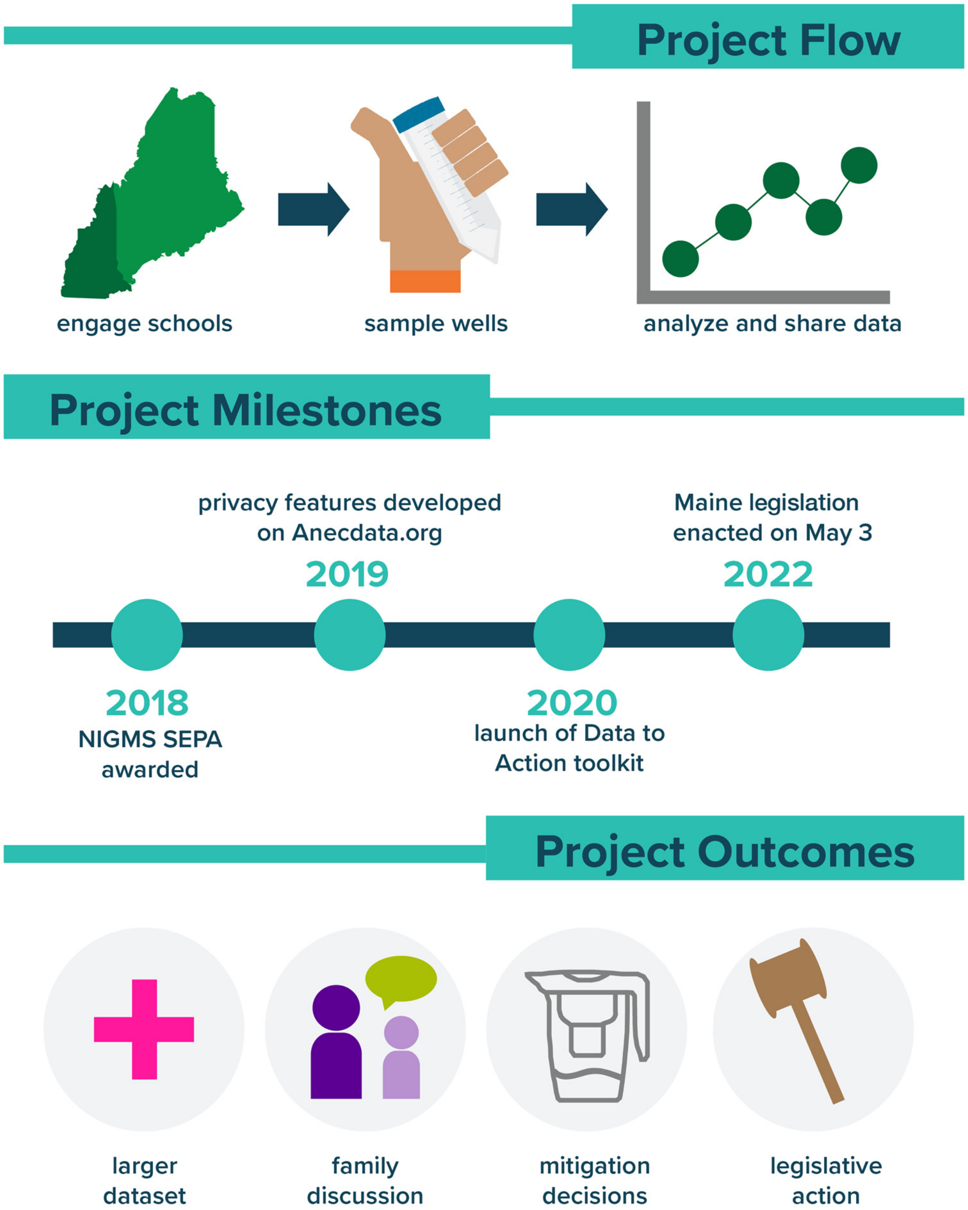


Figure 1. The All About Arsenic Project Information overview: Because arsenic (As) can be found at elevated levels in many wells in Maine and New Hampshire, we created a school-based citizen science project that involved collecting water samples to analyze As and other toxic metals and communicating data in affected communities. Project outcomes with potential for public health impacts include a large publicly available dataset, family conversations and decisions to mitigate exposure, and student input to legislative decision-making (e.g., funds for eligible owners of single-family homes or landlords with private well water to mitigate contamination). Note: NIGMS SEPA, National Institute of General Medical Sciences Science Education Partnership Award.

mitigation action by some project participants, and student influence on legislative action.

The AAA program started as a pilot project with 7 middle and high schools (US EPA NE-83592001, 2016–2017). The project expanded to include 19 additional middle and high schools over the next 5 y [National Institutes of General Medical Sciences (NIGMS) Science Education Partnership Award (SEPA) 1R25GM129796, 2018–2023], emphasizing data literacy and public health goals. The project is ongoing with a second grant that has an additional focus on science communication and intergenerational learning, as well as a plan to address elevated levels of other toxic metals in well water, such as uranium (U), lead (Pb), and manganese (Mn), identified in water tested by the AAA program [National Institute of Nursing Research (NINR) SEPA 1R25NR021077, 2023–2028]. The program involves professional development for teachers and scientist partners working together to plan classroom-based projects associated with drinking water quality. Although teachers embed the project in different courses, including earth science, biology, and chemistry, they all provide the same introduction to the issue of drinking water contamination with toxic metals that are naturally occurring in bedrock found across Maine and New Hampshire. All teachers in the program engage their students as citizen scientists in collecting well water samples from their homes and work with scientist partners who support project implementation, data analysis, and dissemination of information to their communities. Information about each drinking water sample is entered into the citizen science data portal, Anecdata, by teachers or students. Teachers send the water samples to the Trace Element Analysis Core (TEAC) at Dartmouth College, Hanover, New Hampshire, for analysis of As and other toxic metals. The resulting metals data are linked to the drinking water sample information in Anecdata and then transferred to a custom platform created for the AAA project by the data literacy company, Tuva. Finally, with assistance from their teachers and scientist partners, students analyze their well water data using Tuva software and share the results with their communities to raise awareness and move "data to action" by encouraging additional testing and mitigation of As in drinking water. This project is both relevant and motivating for students; it has generated a publicly available dataset that can be used to inform public health decision-making while providing the opportunity for students to contribute to public health goals in their states.[25]

Although the AAA project was designed to achieve both education and public health goals, the present study was focused on our assessment of the public health impacts of this school-based citizen science effort in its first 6 y. In this paper, we report the public health impacts of the AAA program by analyzing the AAA well water dataset relative to municipal- and state-level information on well water contaminants and through findings from surveys and interviews of people who provided well water samples.

Methods

To accomplish public health goals over the first 6 y of the project, we recruited teachers, partnered them with local scientists, and encouraged data sharing through community outreach and education. We analyzed the student data relative to state datasets and used a mixed methods study approach to assess the impact of these efforts on public health.

Teacher and Scientist Partner Recruitment

Between 2016 and 2022, we recruited teachers from across Maine and New Hampshire to cover a wide array of geographic areas (Figure 2). We paired each teacher with a scientist partner from a nearby college or university to provide support for project implementation, data analysis, and community outreach. Two of these scientist partners, one from the College of the Atlantic in Maine and one from Colby-Sawyer College in New Hampshire, also implemented well water sampling efforts with their undergraduate students. Their data are included in the AAA dataset on Anecdata.[26]

We recruited teachers using several approaches. First, we contacted teachers at schools in areas at risk for elevated As who had previously worked with us on other education-related projects. At-risk regions were determined by looking at US Geological Survey (USGS) reports on As risk[27,28] and the results of As testing in publicly available online data portals.[4,5] These teachers recommended or recruited other teachers they thought would be interested in the program. MDI Biological Laboratory, Bar Harbor, Maine, is the lead institution in Maine for the National Institutes of Health (NIH) IDeA Network of Biomedical Research Excellence (INBRE) program, and Dartmouth College is the lead institution for the New Hampshire INBRE program. We contacted INBRE partner colleges and universities to identify scientists interested in working with schools in their communities on this well water monitoring effort. Some of these scientists identified and recruited additional teachers from their communities.

Well Water Sample and Data Collection

Teachers assembled water sample kits that included a 50-mL conical tube with a preassigned sample number label, a strip of Parafilm to seal the tube after sample collection, a refrigerator magnet with a matching label to help families keep track of their sample number, a cover letter with permission to have a water sample analyzed (see Supplemental Material, "SEPA Parent Letter with Permissions)" a datasheet (see Supplemental Material, "Datasheet for Drinking Water Sample Collection"), and instructions for sample collection (see Supplemental Material, "Sample Collection Protocol 2023–2024"). Students took one or more of the water sample kits home and collected a single drinking water sample from their own home and in some instances, from the homes of neighbors or other community members. Occasionally, a student collected a second sample from their home or a neighbor's home at the teacher's discretion. At the time of sample collection, information about each water sample was recorded by the student or homeowner on an individual datasheet. Data fields included the water sample number, the physical address of the sample, and contact information for the person receiving the results (e.g., student's parent, guardian, neighbor, or other community member). The datasheet originally asked participants to select the type of well serving the property (e.g., drilled well, driven well, dug well, boiling spring, public water, I don't know); this has been revised for clarity. In its current iteration, the well type has been changed to drinking water source, and we have clarified the types of public water sources and added "I don't know my drinking water source" as a choice (see Supplemental Material, "Datasheet for Drinking Water Sample Collection"). Other information recorded on the datasheet included the location from which tap water was collected (kitchen, bathroom, outside, other), knowledge of previous As testing (yes or no), information about household water filtration (e.g., no filter, sink-mounted filter, water pitcher or refrigerator filter, whole-household filter), and whether the sampler chose to leave the filter in place or bypass it for collection of the water sample (yes, no, I don't know). The parent/guardian or another sampler, such as a neighbor or other community member, decided whether to collect a filtered or unfiltered sample. If the sample was collected by another sampler, they signed the permission form. We initially required a signature on both the permission form and the datasheet for samples to be analyzed. Currently, we only require the signature on the permission form, to which we have added the acknowledgment that the information on the datasheet is correct, including

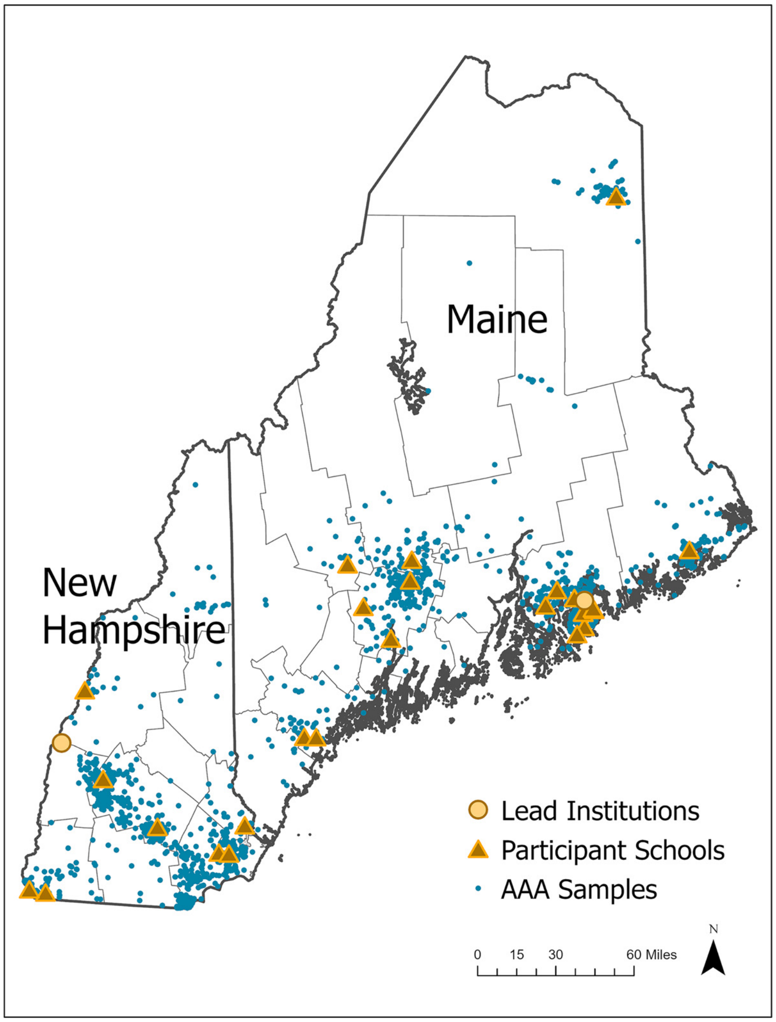


Figure 2. School locations and water sample distribution in Maine and New Hampshire in the All About Arsenic (AAA) project. MDI Biological Laboratory in Bar Harbor, Maine, and Dartmouth College in Hanover, New Hampshire, are the lead institutions in this study. Gray lines are county lines.

additional permission to share private data with public health agencies for further outreach and to share exact location information with other researchers for mapping or additional studies.

Upon receipt of the water samples and completed forms, teachers worked with students to register their samples. This entailed entering the information on their datasheets into Anecdata, a data portal created at MDI Biological Laboratory to facilitate the management and public sharing of citizen science data. For the AAA project, we created privacy features that obfuscate the location of participating households and obscure the names and mailing addresses of parents and students.[29]

Well Water Analysis for Trace Metals

Water samples were shipped to the TEAC at Dartmouth College for analysis, along with a sample manifest and the completed and signed paper datasheets. Upon arrival at Dartmouth, the datasheets were checked against the information on the manifest and Anecdata to ensure they matched. Where discrepancies existed, the information on the paper datasheet was used.

TEAC participates in the USGS proficiency program for water quality measurements, which conducts an interlaboratory comparison study semiannually.[30] Well water samples collected by students were acidified at 0.5% vol/vol with trace metal grade nitric acid (HNO_3) prior to analysis by inductively coupled plasma mass spectrometry (ICP-MS; Agilent 8900). The samples were analyzed in helium mode for As, barium (Ba), beryllium (Be), cadmium (Cd), chromium (Cr), copper (Cu), iron (Fe), Mn, nickel (Ni), lead (Pb), antimony (Sb), selenium (Se), U, and zinc (Zn). The ICP-MS was calibrated with National Institute of Standards and Technology–traceable standards, and the calibration was verified by a second source calibration check, which was run after calibration and every 10 samples. A USGS water proficiency sample was also run as a quality control sample. Duplicate and spiked samples were also run at a frequency of 1 of each per 20 samples. The methods follow US EPA 6020A.[31] Average quality control data over 4 y of analysis were 97%–109% recoveries for USGS proficiency water samples and 96%–103% recoveries for analytical spikes. Averages for duplicate analysis were <20% relative difference except for elements frequently present at concentrations near the instrument detection limits (Be, Cr, Se, Cd).

Notification of Results

After analysis at TEAC, sample results were sent in an Excel file to MDI Biological Laboratory, where they were uploaded to Anecdata and paired with sample registration information. Then, teachers notified sample contributors to use the Lookup Tool on the AAA project website for easy access to their individual well water test results.[32] All households with exceedances of one or more well water contaminants received a personal letter explaining their results and information, such as state-produced literature specific to their contaminant, to aid them in considering next steps (see Supplemental Material, "Cover Letter and Results Report Example"). For As, the MCLs differ for Maine and New Hampshire. New Hampshire lowered its MCL to 5 ppb in 2017,[33] whereas Maine continues to use the US EPA MCL of 10 ppb to regulate public water systems. In this study, all Maine and New Hampshire households received a notification letter when their well water samples exceeded 5 ppb As or the US EPA primary or secondary MCL for any other toxic metal contaminant.

Dissemination of Results to Communities by Schools

After analyzing the data using Tuva data literacy software and preparing outreach materials, teachers and students at each school planned and implemented community education efforts. Information on As in wells was shared by students and teachers with their communities in different ways. Some put information in their school newsletter and engaged other classes or schools in their community to collect water samples. Others planned public meetings. One school presented its findings each year to its board of selectmen. Another school made displays for their municipal building on election day. Some students submitted letters to the editor of their local papers or provided public testimony supporting legislative action to promote well testing and contaminant mitigation. In these and other ways, teachers and students communicated to stakeholders that local wells are at risk for As and other toxic metal contaminants and that regular exposure to these contaminants can lead to negative health outcomes.[25]

Well Water Data Preparation

In November 2022, we downloaded the publicly available AAA project dataset from Anecdata to compare student data collected between 2016 and 2022 with existing state agency datasets on the Maine Tracking Network[4] and the New Hampshire DHHS Data Portal.[5] The Maine Tracking Network comprises all private well water test results submitted to the state Health and Environmental Testing Laboratory (HETL) between 1999 and 2019. They do not include any test results from private labs and, therefore, only represent well owners who choose to test at HETL. Likewise, private well water testing data in the DHHS Data Portal consists of water quality results from the New Hampshire Public Health Laboratories and New Hampshire Department of Environmental Services for 2006–2020 and do not represent data from private labs.

ArcGIS Pro (version 3.0.2), a software that supports data analysis by creating maps that can be layered with other location data, facilitated the comparison between these datasets and the AAA dataset. The full AAA dataset and the code used to analyze the data described below are available from the Environmental Data Initiative under edi.1253.2.[34]

We excluded from the analysis 281 samples that did not have any well water test results. These samples were registered on Anecdata, but analyses were not conducted for various reasons, the most common of which were the lack of a permission form or a missing signature from a parent or guardian. In addition, we excluded samples designated as public water for analyses of AAA program data compared with state agency data. Some well types designated as "other" were identified in the notes section of the datasheet. These were, for example, community wells, artesian wells, springs, and shared wells. We included these samples in our map analyses and other analyses of drinking water samples.

Our analyses included samples from well types designated as "I don't know." At the time of sample collection, participants were asked to identify their well type on the sample datasheet by choosing one of the multiple response options described above, including "I don't know." We sorted the data from those who designated their well types as "I don't know" and determined the percentage with an As level greater than the US EPA limit of 10 ppb or the New Hampshire limit of 5 ppb to conclude that these samples were likely from wells and that they should be included in the analysis. In preparation for mapping, we generated descriptive statistics on the AAA dataset and determined the maximum As level by town. We also identified towns where $>10\%$ of samples exceeded MCLs, and we compared these to those identified in the Maine Center for Disease Control and Prevention (CDC) and New Hampshire DHHS datasets.

Well Water Data Analysis

We compared datasets spatially using geographic information systems (GIS) analysis. We started by importing datasets as comma-separated values (CSV) files into ArcGIS Pro (version 3.0.2). The AAA dataset, the Maine Tracking Network dataset, and the New Hampshire DHHS Data Portal dataset were joined to state municipality shapefiles using town name as the primary key. We used the "Maine Town and Township Boundary Polygons Dissolved" shapefile from the Maine Office of GIS (MEGIS),[35] and the "New Hampshire Political Boundaries at 1:24,000 Scale" shapefile from the Earth Systems Research Center at the University of New Hampshire.[36] After the data were joined, these shapefiles were saved as new shapefiles.

To compare the datasets, we identified towns with well water data from our AAA and state private water datasets, which included 162 towns in Maine and 107 towns in New Hampshire. We determined the distribution of sample data from the AAA dataset and the state datasets by applying a code for towns and grouping them in the following categories: *a*) Maine Tracking Network samples only, *b*) New Hampshire DHHS Data Portal samples only, *c*) Maine Tracking Network samples or New Hampshire DHHS Data Portal samples and AAA samples, *d*) AAA samples only, and *e*) no samples. For the towns in category 3, we compared the number of samples collected in the AAA program to the number of samples collected by the respective state program to analyze the percentage change in the number of samples in those towns using the following formula: percentage change $= [(V2 - V1)/V1 \times 100]$, where $V1$ is the count of CDC (or DHHS) samples; $V2$ is the count of CDC (or DHHS) samples plus the count of AAA samples.

We compared maximum As values for towns in both state datasets with the maximum As values in our AAA dataset. Then, we mapped maximum As values for towns with one or more well water samples in our dataset and highlighted towns where the AAA dataset revealed a higher maximum As level than had previously been reported in state datasets. In addition, we compared the AAA dataset to the state datasets to look for overlap in the towns where $\geq 10\%$ of wells exceeded the state MCL. Again, using ArcGIS Pro (version 3.0.2), we mapped As levels for towns where the AAA and state datasets revealed $>10\%$ of wells exceeded state MCLs.

To understand variability in As by features of the water sample, we analyzed the data in aggregate to compare water samples from different drinking water sources and under different types of filtration. The data from well water samples and other metadata from the AAA dataset were analyzed in R (version 4.1.2, R Development Core Team). Because the samples were nonnormally distributed, we used a Kruskal–Wallis test[37] to determine whether there were statistical differences in the As concentration by well type (drilled, driven, dug, public water, unknown well type, or other) or by the filtration status (filtered, unfiltered, or unknown) and the specific filtration type (no filter, whole-household, sink-mounted, water pitcher or refrigerator, other, or unknown type). If the Kruskal–Wallis test revealed significant differences, we used the Wilcoxon rank sum test with continuity correction to test for significant differences between individual groups.[37] We used an alpha value of 0.05 for all statistical analyses to assess significance.

Well Owner Pilot Surveys and Interviews

In the summer of 2021, we conducted a pilot survey of well owners or renters ($N = 231$) who contributed water samples during years 1 and 3 of the AAA program to refine the survey for distribution to participants from all years of the program at a later date. This study was approved by the Committee for the Protection of Human Subjects at Dartmouth College (STUDY00032306). The owners/renters surveyed were from both Maine and New Hampshire and had well water test results with exceedances of As >5 ppb (i.e., the MCL for New Hampshire).

Data were collected using a modified version of the Tailored Design Method for surveys.[38] We mailed five solicitations for participation, including a prenotification letter, a first-round survey and invitation letter with a dollar incentive and focus group recruitment postcard, a reminder postcard, a second-round survey, and an invitation letter with a dollar incentive and focus group recruitment postcard, and a final reminder postcard. The focus group recruitment postcard was returned separately from the survey to maintain the anonymity of survey responses. The survey was administered in English only. Paper survey responses were entered into Qualtrics. Numerical data were analyzed using R, and text data were analyzed using Atlas.ti 9.

When we received the returned focus group recruitment cards, we emailed the respondents who had children in the program to ask them to participate in a focus group about the school-based components of the program, and we emailed participants without children in the program to participate in individual interviews. Only one individual who had a child in the program responded to the focus group request; therefore, we interviewed this individual like the other respondents without children in the program. During the interviews, we collected "well water stories" to gain insights on well water testing and treatment decisions, the factors influencing those decisions, and perceptions of water quality. Questions were sufficiently broad to allow unanticipated themes to emerge.

Eight interviews were conducted in January and February 2022 by Zoom or phone, and we also received one email response to the interview questions, resulting in data from nine individuals. With permission, we recorded all interviews using Zoom. The average interview length was 27 min. Interviews were conducted by one or two interviewers in English. Field notes were taken after each interview and recorded in a Google document. In addition, we offered to mail a 10-cup (2.4 L) ZeroWater filtration pitcher to participants' homes as a thank-you gift. These filtration pitchers were selected as the gift because, when maintained properly, they remove As from drinking water.[39] Interviews were then transcribed using Temi, a speech-to-text transcription service. We reviewed each interview transcript and, when necessary, relistened to the interviews to check the accuracy of the transcription. We then uploaded transcribed interviews and the email interview to Atlas.ti 9 for analysis. K.H.B. conducted the analysis and reviewed the findings with the other interviewer to ensure consistency in interpretation across interviewers.

Well Owner Pilot Survey Design

Before designing the survey, we devised a framework for assessing owner behaviors and the factors that may influence those behaviors. The framework was informed by research conducted at the Columbia Superfund Research Program, which explored the relationship between latent factors and well water testing and treatment decisions in Maine and New Jersey.[15–17,40–42]

Independent variables included knowledge about As, perceived water quality, perceived risk from As, capacity to address As in drinking water, program visibility (related to the AAA program), As levels, and various demographic factors. Our dependent variables were actions to remediate As from well water before and after participation in the AAA program. We also asked several open-ended questions that provided rich text data about the program and program impact. Open-ended questions included the following:

- If you did not take any arsenic-related action AFTER participating in the *All About Arsenic* project, why not? Check the box that applies. If "other", please describe.
- Please tell us more about your decision to treat or not treat your well water. We are trying to understand how to best support households that have arsenic in their well water.
- Please use the space below for additional feedback for the researchers or *All About Arsenic* project leaders.

Given that the purpose of the present study was to assess public health outcomes, we report on survey responses related to respondents' remediation behaviors, or the lack thereof, not the model explaining the factors influencing their behavior.

Survey Descriptive Analysis

We used R to generate basic descriptive statistics (e.g., frequency tables). The descriptive output provided us with respondents' demographic information and assisted us with identifying the types of remediation and mitigation actions people took before and after the program. R notebooks were created to keep track of the analysis process and to support communication among researchers.

Interview and Survey Text Analysis

To analyze the interviews and survey text data, we first created a codebook based on the themes identified in our field notes and the latent constructs within our framework (e.g., risk, water quality).[43,44] Themes also emerged during the text analysis process (i.e., the cost–benefit analysis in decision-making), and we revised our codebook accordingly. Each code was accompanied by a code description to help ensure consistency of coding across transcripts. After developing and refining our codebook, we coded each interview transcript and survey text data. After completing the coding, we reviewed the codes and related quotations for meaning and insights. For this study, we report on the portion of the analysis that helped us understand the impact of the project on decision-making regarding mitigating As exposure and the factors that may influence that decision-making.

Results

Analysis of Student Well Water Data

Students involved in the AAA program and undergraduates from two partner institutions, the College of the Atlantic and Colby-Sawyer College, collected 3,070 drinking water samples between 2016 and 2022, which were analyzed for As and other toxic metals.[26] The full breakdown by types of drinking water samples is in Table 1.

Of the collected samples, 753 water samples were collected from unknown or other well types from Maine and New Hampshire. We suspect that many or all of the unknown samples were indeed well water given that 130 (17.3%) exceeded the 10-ppb US EPA MCL for As and 204 (27.1%) exceeded the more stringent 5-ppb New Hampshire MCL for As, levels that would not be expected if these were public water sources. In fact, these numbers are higher than those for all known well types. Of the 2,148 samples from Maine and New Hampshire designated as drilled, driven, or dug wells, 323

Table 1. Number of measurements and arsenic (As) values by state and selected variables in analyses of drinking water samples contributed to the All About Arsenic project between 2016 and 2022 [total samples ($N = 3{,}070$)].

Sample description	Samples (n)	Maine	New Hampshire	<5 ppb As	5–10 ppb As	>10 ppb As	Median (ppb) (min–max)
State							
Maine	1,583	1,583	0	1,213	158	212	0.81 (0.00–717.91)
New Hampshire	1,487	0	1,487	1,105	141	241	1.04 (0.00–197.49)
Sample type							
Drilled well	1,900	1,027	873	1,391	211	298	1.10 (0.00–717.91)
Driven well	67	33	34	60	4	3	0.53 (0.00–19.90)
Dug well	181	86	95	151	8	22	0.40 (0.00–108.58)
Public water supply	164	97	67	162	2	0	0.21 (0.00–5.45)
Spring	5	4	1	5	0	0	0.19 (0.06–0.61)
Unknown or other	753	336	417	549	74	130	1.24 (0.00–200.42)
Filtration status ($n = 2{,}906$)[a]							
Filtered	875	391	484	675	81	119	0.84 (0.00–717.91)
Unfiltered	1,543	911	632	1,145	159	239	0.98 (0.00–233.49)
Unknown	488	184	304	336	57	95	1.49 (0.00–197.49)
Filtration type ($n = 2{,}906$)[a]							
Other	41	22	19	27	4	10	0.73 (0.00–717.91)
Sink-mounted	65	36	29	45	4	16	1.16 (0.00–135.05)
Unfiltered	1,543	911	632	1,145	159	239	0.98 (0.00–233.49)
Unknown	488	184	304	336	57	95	1.49 (0.00–197.49)
Water pitcher or refrigerator	62	24	38	51	3	8	0.57 (0.00–70.48)
Whole-household	707	309	398	552	70	85	0.84 (0.00–168.62)
Total	3,070	1,583	1,487	2,318	299	453	0.89 (0.00–717.91)

Note: Sample type, filtration status, and filtration type were reported by the homeowner or renter. Max, maximum; min, minimum.

[a] Public water system samples ($n = 164$) were excluded.

(15%) exceeded the 10-ppb US EPA MCL for As, and 546 (25%) exceeded the more stringent 5-ppb New Hampshire MCL. In comparison, of the 164 samples designated as "public drinking water supply," only 2 exceeded the 5-ppb New Hampshire MCL (5.4 and 5.2 ppb). Therefore, we included the data from the water sources designated as "I don't know" in our analyses of wells.

Adding this student-derived well water data to existing datasets from the Maine Tracking Network and New Hampshire DHHS Data Portal significantly increased the number of wells tested in many towns, revealing the capacity for this school-based citizen science approach to improve well testing rates and provide new public health knowledge (Figure 3; Excel Table S1). There was a notable percentage change in the number of samples by town when the AAA dataset was added to state datasets. In both Maine and New Hampshire, there were four towns where the percentage change was >100%, meaning the number of samples more than doubled when adding student samples to the state dataset (Figure 3, Table 2; Excel Table S1). Also notable were three towns where Maine CDC had no samples, and the AAA dataset contributed 1–2 samples, so students were able to access

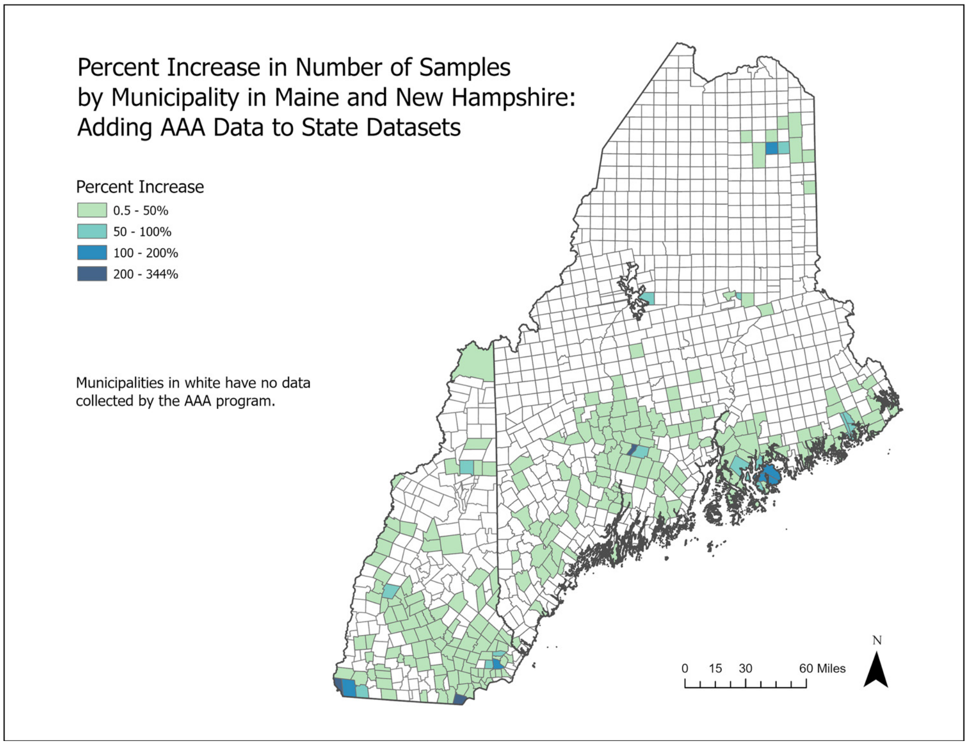


Figure 3. Percentage change in numbers of well water samples when adding All About Arsenic (AAA) data to existing Maine Center for Disease Control or New Hampshire Department of Health and Human Services data. Numeric data can be found in Excel Table S1.

Table 2. Towns in Maine and New Hampshire where student efforts in the All About Arsenic (AAA) project more than doubled the total number of wells tested, 2016–2022.

State	Town	CDC or DHHS samples (*n*)	AAA samples (*n*)	Increase (%)
Maine	Waterville	35	106	303
Maine	Bar Harbor	175	304	174
Maine	Castle Hill	2	3	150
Maine	Mount Desert	101	128	127
New Hampshire	Hinsdale	9	31	344
New Hampshire	Pelham	121	362	299
New Hampshire	Winchester	15	32	213
New Hampshire	Exeter	23	31	135

Note: CDC, Maine Center for Disease Control and Prevention; DHHS, New Hampshire Department of Health and Human Services.

towns that had little or no publicly available information on As and other metals in local wells. When people contributed well water samples to the AAA program, they were asked permission to share their data with the Maine CDC or the New Hampshire Department of Environmental Services. Among those participants who indicated their preference on the datasheet, ~90 percent from Maine and New Hampshire permitted their data to be shared. Maine CDC plans to integrate shared data from the AAA dataset into the Maine Tracking Network in the coming year. New Hampshire is considering including these datasets in the DHHS Data Portal in future versions of the Well Water Dashboard.

Maximum As levels, as well as the percentage of samples that exceed MCLs, are metrics that state agencies use to identify priority areas for community outreach and education to reduce exposure and to recommend specific actions. For example, when a well exceeds 100 ppb of As, state health agencies may advise that well owners reach out to a state expert for additional guidance and support, including risks from exposure routes other than primary ingestion, such as bathing, and discussions around point-of-use vs. point-of-entry treatment systems.[45–48] We looked at how the MCLs found in the AAA project compared with the MCLs found in the Maine Tracking Network and New Hampshire DHHS Data Portal (Figure 4; Excel Table S2). In all municipalities where we found an MCL of >100 ppb, state agencies were already aware that some households in that area had well water with high levels of As. In seven municipalities in Maine and nine in New Hampshire, the AAA dataset revealed higher maximum As levels in well water than previously had been identified. In some cases, these new maximum values for towns exceed state MCLs; in one case, there had not been a known exceedance of the MCL in the town before the AAA project.

Our data mirrors Maine CDC and New Hampshire DHHS data for the percentage of households per town with exceedances of state MCLs (Figure 5; Excel Table S3). The towns in the AAA dataset with >10% of households with MCL exceeding 10 ppb (Maine) or 5 ppb (New Hampshire) were also evident in the Maine CDC and New Hampshire DHHS datasets as towns with >10% of households exceeding those MCLs.

Overall, 15% ($n = 323/2{,}148$) of identified wells (dug, driven, and drilled) in the AAA dataset and 14.8% ($n = 453/3{,}070$) of all drinking water samples exceeded 10 ppb As, the national US EPA MCL that is currently used in Maine, whereas 25.4% ($n = 546/2{,}148$) of wells and 24.5% ($n = 752/3{,}070$) of water samples in the AAA dataset exceeded 5 ppb, the MCL set by New Hampshire (Table 1). Notably, this means that the drinking water of 10.4% ($n = 223/2{,}148$) of households with wells and 9.7% ($n = 299/3{,}070$) of all households fall between 5 and 10 ppb As (Table 1). This reveals that hundreds of households from which students collected samples were at risk of chronic exposure to As levels deemed safe for drinking in one state but not another.

Students collected metadata for their well water samples, revealing information about homeowners' knowledge of their

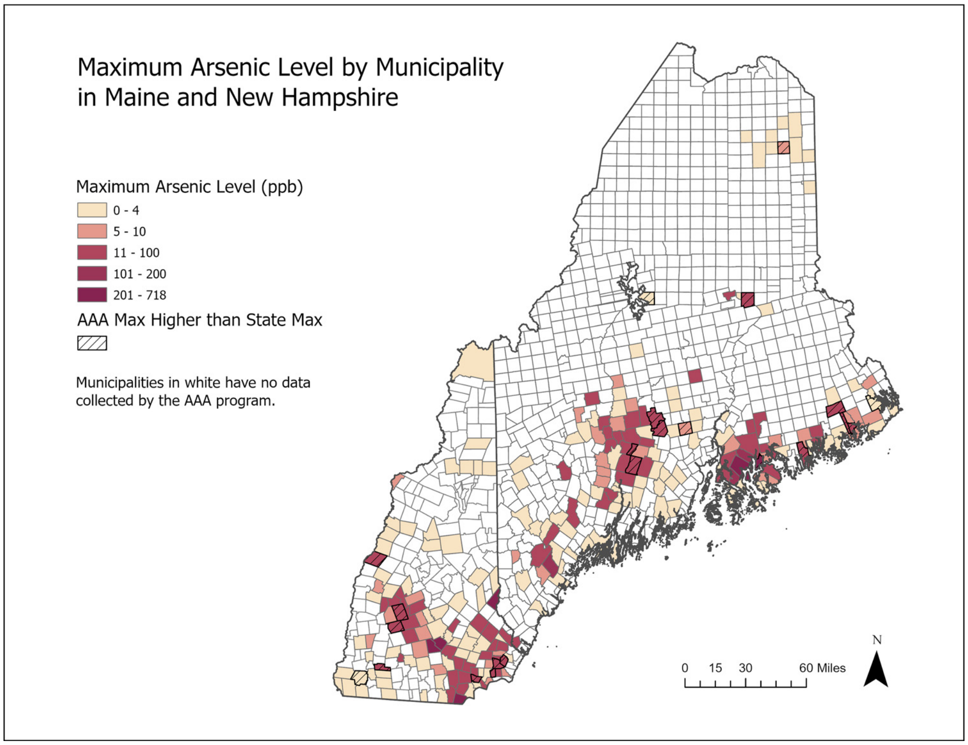
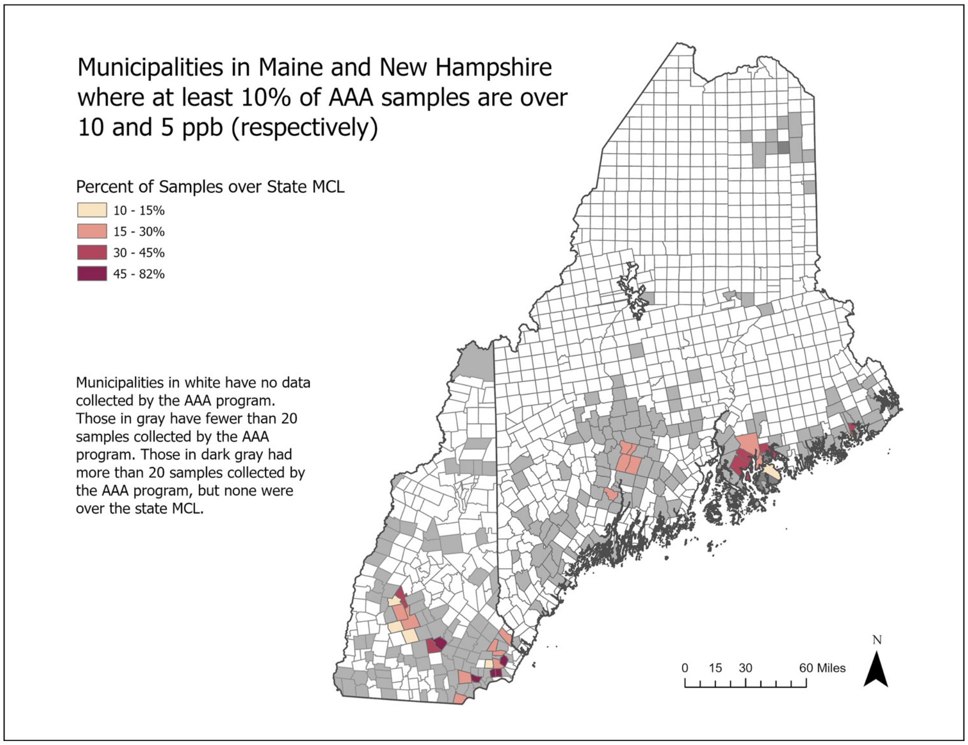


Figure 4. Maximum levels of arsenic (As) in well water samples collected for the All About Arsenic (AAA) project. The towns where the highest detected levels exceeded maximum contaminant levels (MCLs) identified by the Maine Center for Disease Control or the New Hampshire Department of Health and Human Services are outlined and hatch-marked in black. Note that Maine and New Hampshire have different MCLs (10 ppb and 5 ppb, respectively). Numeric data can be found in Excel Table S2.



Municipalities in white have no data collected by the AAA program. Those in gray have fewer than 20 samples collected by the AAA program. Those in dark gray had more than 20 samples collected by the AAA program, but none were over the state MCL.

Figure 5. Towns where >10% of wells exceed the maximum contaminant level (MCL) of 10 ppb for arsenic (As) in Maine and 5 ppb for As in New Hampshire. All About Arsenic (AAA) study results are similar to state agency data for the percentage of wells exceeding the MCL in each municipality. Numeric data can be found in Excel Table S3.

wells and additional details related to contamination of drinking water with As and other toxic metals. Most residents who contributed water samples to the AAA program reported getting their drinking water from drilled, driven, or dug wells (70.0%, $n = 2{,}148$); the remainder reported getting their drinking water from public, unknown, or other sources (30.0%, $n = 917$). As expected, the median As concentrations of public water supplies, which are regulated, were significantly lower than those for all categories of wells (Figure 6, Table 1; Excel Tables S4 and S5). In addition, the median As concentrations of water samples from drilled wells and unknown or other well types were higher than those of water samples from driven wells (Figure 6, Table 1; Excel Tables S4 and S5). Importantly, drilled wells in the AAA dataset had significantly more As than other well types or water sources, which is explained by the As-laden metasedimentary bedrock common throughout Maine and New Hampshire. The dug wells had more As than anticipated (Figure 6; Excel Tables S4 and S5). Although geology explains most As contamination in groundwater,[49] the fact that some dug wells had elevated As has raised the question of whether As is getting into drinking water from surface contamination, perhaps from the historical use of arsenical pesticides in the region,[2] or whether irrigation water from drilled wells with elevated As contaminates dug wells.

In addition to information on drinking water source and well type, students collected information on filtration when sampling their home drinking water. The filtration status and type of filter were not always known. The data analysis revealed a significant difference in median As levels for the water samples identified as filtered (0.84 ppb, $n = 875$) and those identified as unfiltered (0.98 ppb, $n = 1{,}543$, $p = 0.004$; Figure 7A; Excel Tables S6 and S7). Further, there are statistically significant differences between the median As levels of samples with unknown filtration status (1.49 ppb, $n = 488$) and both samples that were filtered ($p < 0.0001$; Figure 7A; Excel Tables S6 and S7) and unfiltered samples ($p < 0.0001$; Figure 7A; Excel Tables S6 and S7). Samples with unknown filtration status had median As levels 0.65 ppb higher than the filtered samples ($p < 0.0001$) and 0.51 ppb higher than the unfiltered samples ($p = 0.0015$; Figure 7A; Excel Tables S6 and S7). When investigating the impacts of specific types of filters (Figure 7B; Excel Tables S8 and S9), we found samples filtered with whole-household filters (0.84 ppb) or water pitcher/refrigerator filters (0.57 ppb) had significantly lower median As levels than unfiltered samples (0.98 ppb, $p = 0.018$ and $p = 0.0007$, respectively). We did not detect significant differences between unfiltered samples and those from sink-mounted filters (1.16; $p = 0.73$). Importantly, when comparing samples with unknown filtration systems to those with known filtration types, the samples with unknown filtration types had significantly higher median levels than samples filtered with whole-household filters (1.49 vs. 0.84, $p < 0.0001$) or with water pitcher/refrigerator filters (1.49 vs. 0.57, $p < 0.0001$) but as noted above, had significantly higher As levels than samples that were not filtered.

Beyond As, we are also learning other valuable public health information. For example, the well water samples collected by students were analyzed for other metals in addition to As. The results revealed that other metals, also of concern across Maine and New Hampshire, are elevated in many wells (Table 3).

Results of Teacher Recruitment, Sample Collection, and Outreach by Schools

In the time span of data collection presented in this paper, 31 teachers from 27 middle and high schools in Maine and New Hampshire participated in the AAA program. Between 2016 and November 2022, 4,859 students were involved in the program. Students collected 2,877 water samples for analysis of As and other toxic metals (Excel Table S10), some from private wells, public water supplies, and other sources. These numbers do not

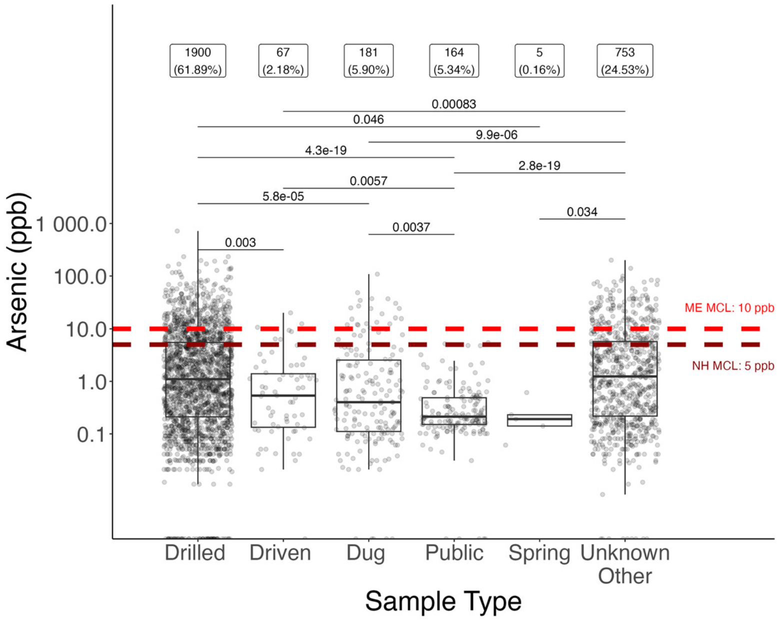


Figure 6. A comparison of drinking water sources from which students collected samples in Maine and New Hampshire for the All About Arsenic project, 2016–2022. Unknown/other includes those who did not know the source of their drinking water and rare well types that do not fit in other categories. The label above each *x*-axis category indicates the number of samples for each well type and the percentage of the water samples it represents. Each box shows the IQR, with a thick black horizontal line indicating the group median. The upper whisker indicates the third quartile plus 1.5 × IQR, whereas the lower whisker indicates quartile 1 minus 1.5 × IQR. The *y*-axes are on a $\log_{10}$ scale for easy visual comparison. To facilitate plotting on the log scale, all values are increased by 0.001 to avoid infinite values. An alpha value of 0.05 was considered statistically significant. If there is no line between two box and whisker plots, there is no significant difference between them. Numeric data and statistics for this figure are found in Excel Tables S4 and S5. Note: IQR, interquartile range.

include contributions from the College of the Atlantic in Maine and Colby-Sawyer College in New Hampshire. However, the well water sample data collected by their undergraduates for the AAA project are included in analyses of well water samples.

As part of the program, teachers and students not only collected well water samples for analysis but also conducted outreach events and activities. Most teachers did not quantify the number of people reached through each activity. Some activities were impossible to quantify because they involved the submission of newspaper articles or letters to the editor, presentations at municipal meetings, or testimony at public hearings that were televised. In all contexts, the outreach content presented included the effect of As and other toxic metals on human health, the reasons why this is a particular issue in Maine and New Hampshire, findings by students in their communities, and information on mitigation. Some examples of outreach activities where teachers reported numbers of people reached are described below:

In 2019 students from Pinkerton Academy in Derry, New Hampshire, distributed 100 flyers at the Londonderry, New Hampshire Hazardous Waste Collection Day to encourage people to think about their drinking water and potential contaminants and offered "best management practices" for well water protection. Field trips were canceled in 2020 and 2021 due to the pandemic; however, students developed a public service announcement and outreach materials that were distributed throughout the school. They resumed distributing flyers on the Hazardous Waste Collection Day in 2022.

In 2019, a community event in Waterville, Maine was hosted by multiple teachers involved in the AAA program. The event drew 60 participants from the surrounding area. After a shared dinner, students presented posters and talks and engaged community members, fellow students, and teachers in discussing healthy drinking water, possible sources of water contamination, and recommended mitigation measures.

In Machias, Maine, during the 2020–2021 school year, a Machias Memorial High School teacher engaged students in writing a newspaper article inviting the community to participate in the AAA program. In addition, information and test kits were supplied to a local pediatrician to disseminate to patients. Students distributed test kits to interested community members; 14 were returned for analysis. Six samples were received from the pediatrician. A well water sample from a household with a newborn baby was found to have 35 ppb of As.

In 2022, students from Pelham High School in New Hampshire went to Pelham Elementary School on each of four nights of parent–teacher conferences, displaying and handing out information about well water contamination with As and other toxic metals. They distributed 100 well water test kits to families, 86 of which were returned for analysis.

In November 2021 and 2022, Conners Emerson Middle School students from Bar Harbor, Maine were at the town's polls on voting day with tri-fold displays and handouts on As, showcasing their data and offering free test kits to community members. Each year, they talked to hundreds of people and distributed many well water test kits, 38 of which were returned for analysis in 2021 and 41 in 2022. In those years, 6% of samples exceeded the US EPA MCL of 10 ppb As.

Results of the Pilot Survey: Participants' Remediation Behaviors

Of the 231 households surveyed, 120 were from Maine and 111 were from New Hampshire (Table 4). After accounting for undeliverable surveys, the response rate was 40% ($N = 79$) across both states. Table 5 provides a summary of demographic data related to the survey respondents. It is important to note that the survey was only distributed to people whose filtered or unfiltered well water test results exceeded 5 ppb. Seventy-two survey respondents reported on their actions to address As in their well water before and after participation in the AAA program. Fifty-six (77.8%) respondents acted to remove As from their well water before the program. Of the 56 respondents who reported acting before

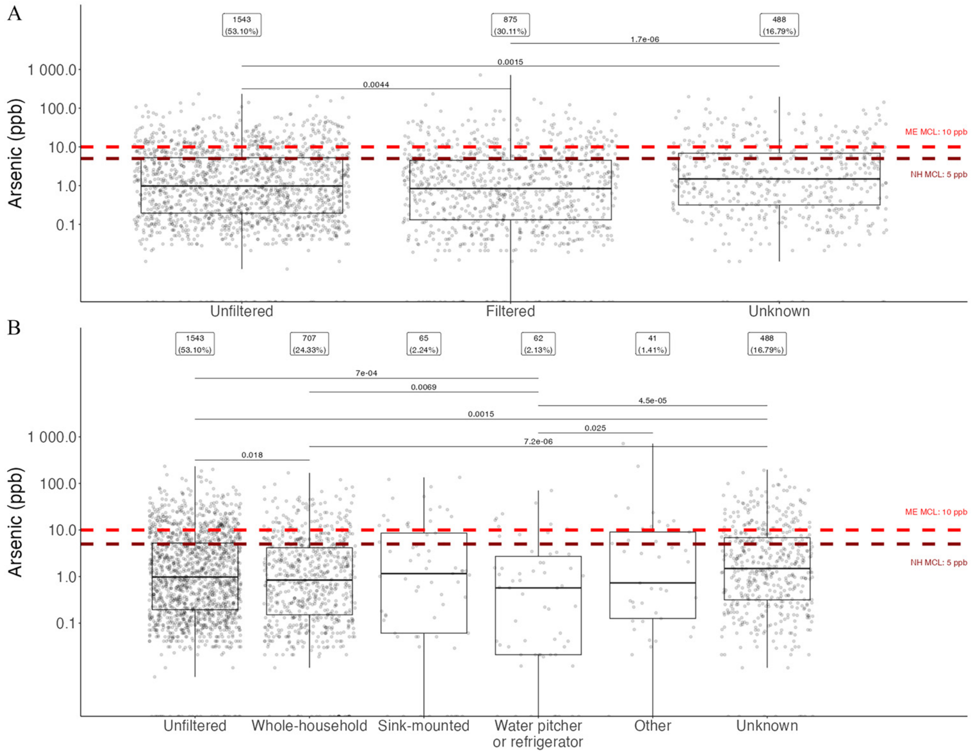


Figure 7. (A) Arsenic levels in unfiltered, filtered, and unknown filtration-status well water samples collected in Maine and New Hampshire for the All About Arsenic project, 2016–2022. (B) Arsenic levels in drinking water samples with no filtration and those filtered through one of the various filtration systems, as reported by residents. The *y*-axes are on a $\log_{10}$ scale for easy visual comparison. To facilitate plotting on the log scale, all values are increased by 0.001 to avoid infinite values. The label above each *x*-axis category indicates the number of samples in that category and the percentage of the water samples it represents. Each box shows the IQR, with a thick black horizontal line indicating the group median. The upper whisker indicates the third quartile plus $1.5 \times \text{IQR}$, whereas the lower whisker indicates quartile 1 minus $1.5 \times \text{IQR}$. An alpha value of 0.05 is considered statistically significant. If there is no line between two box and whisker plots, then there is no significant difference between them. The sum of whole-household, sink-mounted, water pitcher or refrigerator, and other ($n = 875$) corresponds to the category "Filtered" in (A). Numeric data and statistics for (A,B) are provided in Excel Tables S6–S9. Note: IQR, interquartile range.

program involvement, 22 (30.6%) took additional steps (e.g., changed filters, retested water, drank bottled water) after participating in the AAA program. Sixteen individuals (22.2%) reported not acting to remove As from their drinking water before the program. Of that group, 7 (9.7%) respondents took steps to mitigate As exposure after participating in the program, and 9 (12.5%) did not take remediation actions.

Written comments to the open-response questions in the survey yielded insights on why participants did or did not take action to mitigate As after participating in the program. First, there were 36 text comments indicating that respondents already had treatment systems (e.g., point-of-use systems) in place or used practices (e.g., drinking bottled water) to mitigate As exposure before participating in the program. Second, 8 text responses described actions taken after participating in the program and included individuals who had no prior knowledge of As in their well water (e.g., they learned about it through the program) and individuals who had treatment systems or used bottled water and took further

Table 3. Summary of well water contaminants in Maine and New Hampshire wells tested in the All About Arsenic (AAA) project, 2016–2022.

Contaminant	Samples (*n*)	LOD (ppb)	MCL or alert value (ppb)	Wells over MCL/ Alert value (*n*)	Wells over MCL/ Alert value (%)	Median ± SD conc. (ppb)	Maximum conc. (ppb)
Antimony	2,906	0.02	6	5	0.17	0.02 ± 0.69	24.78
Barium	2,366	0.03	2,000	1	0.04	2.47 ± 56.10	2,438
Beryllium	2,901	0.05	4	3	0.10	0.00 ± 0.71	35.36
Cadmium	2,904	0.01	5	0	0	0.00 ± 0.19	4.94
Chromium	2,902	0.05	100	0	0	0.00 ± 0.52	12.77
Copper	2,906	0.03	1,300	27	0.93	13.95 ± 352.09	6,637
Iron	2,903	1.00	300	149	5.13	7.96 ± 4,429.97	235,960
Lead	2,906	0.01	4	153	5.26	0.23 ± 232.87	10,910
Manganese	2,906	0.02	50	395	13.59	2.03 ± 225.24	4,975
Nickel	2,905	0.02	NA	—	—	0.31 ± 26.77	1,107
Selenium	2,903	0.08	50	0	0	0.04 ± 0.1	1.09
Thallium	1,489	0.01	2	0	0	0.00 ± 0.01	0.29
Uranium	2,905	0.01	30	181	6.23	0.76 ± 78.38	3,274

Note: No MCL has been established for Ni. Although all samples were analyzed for As, the other analytes assayed depended on a variety of other factors, some internal to the study and others related to the Trace Element Analysis Core (TEAC). For example, our samples were sometimes run with other samples at TEAC that were being tested for a similar but different array of elements. The sample sizes reflect the number of samples analyzed for that element. —, No data; As, arsenic; conc., concentration; LOD, limit of detection; MCL, maximum contaminant level; NA, not applicable; Ni, nickel; SD, standard deviation.

Table 4. Summary of the surveys mailed, delivered, and returned.

Survey status	Maine	New Hampshire	Both states
Surveys mailed	120	111	231
Surveys undeliverable	24	9	33
Surveys delivered	96	102	198
Surveys returned	31	48	79
Return rate (%)	32	47	40

Note: Data are presented as n unless otherwise noted. The surveys were mailed to households with ≥5 ppb arsenic in well water from years 1 and 3 of the All About Arsenic project.

action after participating in the program. These actions varied but included upgrading systems, installing treatment systems, filling water bottles at other locations, and drinking bottled water.

Importantly, when considering impediments to action, 15 written comments indicated that, for them or their neighbors, cost prohibited certain types of actions, such as installing a whole house system, and influenced their cost–benefit analysis, such as deciding that treatment was not worth the cost if their As levels were only slightly higher than the MCL.

Interview Analysis Results

Following the surveys, we conducted eight Zoom or phone interviews and one email interview with survey respondents to learn additional information about their well water stories and testing and treatment decisions. Table 6 summarizes the key characteristics of the interviewees, including the actions they took before and after participating in the AAA project and how we classified program impact in the analysis. Seven individuals were from Maine and two were from New Hampshire, representing participation from seven different schools across the two states.

Interviews revealed the program's public health, affective (experience of feeling or emotion), and educational impacts. Regarding public health, five interviewees indicated they took specific actions to treat their drinking water after participating in the AAA project. These are classified as direct public health impacts. Three others noted that the project confirmed for them that they still had an As problem prior to filtration but that their filters were effectively removing As; these were all individuals who had filters before participating in the project and tested their unfiltered water only during the AAA project. The confirmation gave them added confidence in their filtration systems and the companies testing and treating their water. These are classified as affective or emotional impacts.[50]

Table 5. Characteristics of pilot survey participants in the All About Arsenic project, 2018–2022.

Characteristic	n (%) unless otherwise noted
Age [mean (y)]	51.4
Gender	
Female	52 (70.3)
Male	20 (27.0)
No response	2 (2.7)
Residence	
Years in home (mean)	13.9
Own home	71 (95.9)
Rent home	2 (2.7)
Other	1 (1.4)
Education	
Associate degree or less	13 (17.6)
Bachelor's degree or more	60 (81.1)
Other	1 (1.3)
Gross household income	
<$80,000	12 (16.2)
≥$80,000	40 (54.1)
Prefer not to answer	17 (23.0)
No response	5 (6.7)
Arsenic in drinking water	
As concentration in the sample (in ppb) [mean (median)]	27.2 (18.2)
All demographic questions skipped	5 (6.3)

Note: $N = 79$; 5 (6.3%) skipped all of these questions; therefore, percentages are based on $n = 74$. In addition to the 5 individuals who skipped all demographic questions, an additional set of individuals selected "prefer not to answer" or skipped one or more demographic questions. Missing demographic data are represented as "no response" to this question.

Finally, five interviewees discussed what we classify as the educational impact of the project on students and the community. For example, they noted that this project helped educate students about drinking water quality and generated interest in community-based research owing to its relevance and real-world implications. In addition, a few participants mentioned that the project was important for educating the broader community about As and its health impacts.

Participants described multiple factors that motivated them and influenced their decision-making when asked to tell their "well water stories" and their reactions or actions when they learned about their elevated As levels. Risk, specifically health risk, was a central theme in the discussion about well water testing and treatment decisions. For three interviewees, the health risks to their children and family were primary concerns. In fact, one individual knew about the As problem when they bought the house but did not treat their water; they became concerned with the As levels when they had a family and finally installed a filtration system. For others, general concerns about the impacts on their personal health dominated their discussion of risk. These expressions were often vague, such as "because arsenic, you know, is not good… the concern, it was health concerns." Others expressed very specific concerns about liver failure, heart disease, and cancer.

Interviews also provided insight into individual decision-making. Although the factors that influenced decisions varied by the individual, some of the factors that interviewees identified included who was drinking the water, how much water was consumed, the frequency of consumption, cost, perceived risks from As, age, and level of As exceedance. Two examples from interviews exemplify the complex decision-making process:

> *I didn't know much about the, the point of use systems and… I didn't use a lot of water, so I didn't know if at the time it would be cost beneficial. I wasn't using that much bottled water. So, I know environmentally, it wasn't really the best idea to use bottled water. But yeah, I just, I decided to keep using the bottled water or very small amounts of my well water.*
>
> *When I found out after this water test that I had high levels of arsenic in my home groundwater, I immediately told my wife and stepdaughter to use bottled water until I could get a filter installed. A couple weeks after the test I installed a "point of use" reverse osmosis filter (iSpring RO500 model) at the kitchen sink. We now use this faucet to pour any drinking water for ourselves and our pets …A point of use filter seemed to be the most realistic solution, I installed this in the kitchen where we drink/cook the most. Whole house solutions were merely unrealistic, and I looked into the "assistance programs" however I did not qualify for any of these income-based options.*

Discussion

Lessons from Well Water Analysis

The AAA program engaged students as citizen scientists in active learning through the collection of well water samples that were analyzed for As and other toxic metal contaminants. The program was relevant to students because a large proportion of the

Table 6. Characteristics of interviewees ($n = 9$) and their actions before and after participating in the All About Arsenic (AAA) project.

State	Date of sample	As level of sample (ppb)	Knowledge of As levels prior to testing	Action before AAA program	Action after AAA program	Type of impact
New Hampshire	February 2021	6.61	No knowledge of As problem	None	None – "As level not that high"	Educational[a]
New Hampshire	December 2020	9.81	No knowledge of As problem	None	Switched to bringing water from a family member's home	Public health[b]
Maine	February 2021	135.1	Knew when bought the house	Changed filters on an existing system	Program was confirmatory	Affective[c]
Maine	May 2019	8.22	Knew exceeded state, but not federal levels	Drank bottled water, cooked with tap water	Used ZeroWater filter pitcher	Public health
Maine	December 2020	9.52	Knew before program	Began researching systems	Took no action, but wants to	Educational
Maine	December 2020	24.96	Knew when bought the house	None	Switched to bottled water and then installed POU System	Public health
Maine	February 2019	185.11	Knew when replacing the filter for another system	Installed POU System	Confirmed As levels	Affective
Maine	December 2020	5.51	Knew when bought the house	Installed POU System	Used ZeroWater filter pitcher	Educational public health
Maine	December 2020	20.28	Suspected when bought the house	Drank and cooked with bottled water	Installed POU System	Public health

Note: As, arsenic; POU, point-of-use (system); ppb, parts per billion.

[a] Educational impact means the resident reported having new information.

[b] Public health impact means household exposure to As was reduced.

[c] Affective impact means the resident reported new or renewed confidence in prior actions to reduce exposure.

population in their home states relied on private wells, and based on geology, these wells had a relatively high likelihood of well contamination with As or other toxic metals.

Student data revealed that there is variation in As levels even in some homes with active filtration. This is not surprising, given that we know there is substantial variability in the ability of tabletop filters to remove As,[39] as well as variability in the capability of commercially available filtration systems to remove As.[51] In our AAA study, some whole-household filtration systems were described as sediment filters. Some homeowners may be unaware that these filters are not designed to remove As. However, we did not ask homeowners what they thought their filters were designed to do; therefore, we are unable to discern homeowners' understanding of filter efficacy. Despite this limitation, we do see that even in the presence of filtration, 13.6% ($n = 119/875$; Table 1) of filtered water samples exceeded the 10-ppb MCL. Alarmingly, 24.6% ($n = 16/65$; Table 1) of samples filtered with sink-mounted filters still have drinking water exceeding the 10-ppb MCL in Maine. Elevated As levels in filtered samples reveal an exposure risk for people who might assume their filters are reducing As levels to a safe amount when they are not. This underscores the importance of regular water testing and filtration maintenance, even when mitigation efforts are in place.

Students learned about As's health effects, developed data analysis skills, and communicated their findings to their families and communities. The growing AAA dataset is of interest to state agencies and holds the potential to impact public health across both Maine and New Hampshire by broadening the reach of well water testing across communities, thereby increasing individual knowledge and strengthening the dataset that informs public health officials' education and outreach initiatives. We have demonstrated that the sheer number of samples collected by students has, for some municipalities, doubled or more than doubled the amount of publicly available data on As in wells.

Elevated levels of other toxic metal contaminants were found in drinking water samples, such as U, Mn, and Pb, each of which can cause various negative health effects. U exposure can cause problems with bone metabolism and structure,[52] kidney function,[53–55] and has been associated with increased risk of leukemia.[56] Exposure to Mn levels in drinking water above the US EPA secondary standard has been reported as a health concern in formula-fed infants[57] and has been associated with attention deficit hyperactivity disorder in children.[58] Pb is a well-known neurotoxin associated with reduced IQ and developmental delays in children.[59] For all these reasons, we plan to expand our focus to include these other metals in our current NINR SEPA project, given that concerns have risen in some communities in response to student findings. Student-derived drinking water data may serve to address environmental justice issues in Maine and New Hampshire. Water treatment options can be expensive; therefore, those who experience low income may be more likely to suffer disproportionately the health effects of exposure to toxic metals. Toxic Metal-Environmental Justice Indices can be used to identify areas at risk for health impacts and prioritize resources for testing and remediation of As and the other metals tested in the AAA project.[60] This approach, coupled with participatory research with affected communities, has been shown to lead to structural change outcomes.[61]

Lessons from Survey and Interview Data

Survey and interview data demonstrated the program has public health, affective, and educational impacts. Specifically, survey data revealed that of the 72 respondents who reported taking action to remediate As, 7 acted for the first time after participating in the project and 15 others took additional steps to improve their filtration. For some of those who knew that they had elevated levels of As in their well water, the program confirmed that As was still an issue and that they needed to continue to monitor their well water. Educationally, the program sparked conversation among parents and children about their drinking water and how it impacts health and increased community-level awareness about the issue. Finally, the interviews revealed that "action" is multifaceted and often involves a process that begins with researching options, contacting well water treatment professionals, and trying different remediation options. By defining "action" as filtration or not drinking contaminated water, the pilot study may have underestimated the program's impact by not capturing antecedent behaviors. A follow-up survey should account for a broader set of actions to assess the program's impact on individual households.

Interviews also revealed that decision-making is complex and that public health programs need to recognize that there is a balance among health risks, costs, and convenience in homeowner testing and treatment decisions. The survey and interviews operated successfully as part of the pilot study in that they revealed issues with survey design and content that need to be addressed before surveying a broader population of AAA participants with well water As exceedances. The data entry and survey analysis processes revealed several areas for survey improvement, including wording changes, problems with the underlying meaning of certain items and constructs, question ordering, and superfluous and missing questions. One of the important limitations of the survey and interview results is that the respondents were primarily college-educated homeowners with higher incomes. It is possible that the findings, such as testing and treatment behaviors prior to and after participation in the program, may be different among different populations, particularly those who may not have the financial means to pay for different mitigation measures, such as bottled water and treatment systems. Future studies should explore mechanisms for reaching a more diverse audience so we can better understand how to positively impact testing and treatment among all community members.

In addition to the results of the pilot surveys and interviews, we have anecdotal feedback that parents are taking action after their child participated in the AAA program. A parent in a town with a significant As issue and a high rate of well water testing sent the following email to the teacher involved in the program, providing additional evidence that, on an individual level, the AAA project is impacting human health:

> *My [child] came home and told us that we were at 50 [ppb] for arsenic after the first test so we put a filter on the drinking water and this 2nd test has us at 0.02. We never would have known if you hadn't done this program.*

Contributions to Other Research

In 2019, students provided duplicate water samples to a graduate student at the University of Maine for use in a bioassay to test the effects of metal mixtures on zebrafish behavior. The results of the study revealed that exposure to a mixture of metals was associated with adverse developmental effects, even when individual metal levels were low.[62] Collaborations with researchers interested in studying the well water samples are another way the AAA program contributes to public health research. Research on the impact of metal exposure on animal health helps inform what standards might be needed to reduce health risks in humans.

Policy Impacts

Another essential metric of public health impact is legislative change. Although advocacy and activism are not the focus of this paper, the AAA program played an important role in recent legislation in Maine. A bill that came before Maine's 130th legislature was LD 1891, HP 1401, *An Act to Continue Supporting Safe Drinking Water for Maine Families*. Using resources provided in a "Data to Action Toolkit" on our project website,[63] students from two schools prepared and provided testimony for public hearings in support of this legislation, which was enacted on 3 May 2022. The legislation enables the Maine State Housing Authority to provide one-time remediation grants to eligible owners of single-family homes or landlords with a private well that shows evidence of contamination. This effort by students and the eventual legislative outcome demonstrates the capacity of advocacy and activism in school-based citizen science programs to effect change.

Conclusion

We believe that a school-based approach to well water testing can "move the needle" to prevent exposure to As and other toxic metals in vulnerable communities where people are unaware of their risk or where other efforts to encourage well water testing have fallen short. Even in communities where there is already broad public knowledge of the potential for contaminants in drinking water, well water testing rates remain low, and programs, such as AAA, can start to effect change. Increasing homeowner awareness of the health risks of toxic metal exposure and related solutions through programs that promote education, testing, and mitigation for As and other toxic metals in well water will remain an important component of the public health strategy in rural states, such as Maine and New Hampshire, where there are considerable risks of exposure to these contaminants in private drinking water.

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