

Public Health Concerns at the Intersection of Drinking Water Contamination and Low Healthcare Access in Maine

by Alexis C. Garretson, Alexandra Duffy, Richard Hilliard, Ashley Taylor, Caitlin Oliver-Olsen, Morgan Karns, and Jane Disney

ABSTRACT

Issues surrounding drinking water quality and inadequate monitoring of metal contaminants are particularly relevant in Maine, where 55 percent of residents rely on private wells for drinking water, yet only half of those wells test for arsenic. The public health impacts of contaminated water can be compounded by limited access to healthcare in rural areas. To better inform state and local policy, we assessed the potential public health risks that arise from the intersection of environmental and structural vulnerabilities. We used a dataset of 2,664 private drinking water samples collected between 2016 and 2025 by Maine students involved in a secondary school-based citizen science project called All About Arsenic. To evaluate the dual burden of exposure to heavy metal contaminants in areas with limited access to healthcare, we analyzed the distribution of metal contaminants in the subset of private well samples relative to health professional shortage areas across Maine.

policymakers think about toxic metals in drinking water, arsenic (As) is usually at the forefront of their minds, as many private wells in Maine draw from bedrock aquifers that contain naturally occurring arsenic (Yang et al. 2009). Inorganic arsenic, which is the most common type of arsenic found in drinking water, is a confirmed carcinogen, and chronic exposure to even low levels of arsenic can cause a variety of health effects (Sinha and Prasad 2020). While the focus on arsenic in drinking water, especially in New England, is well justified, other heavy metals also pose health risks (Rehman et al. 2018).

INTRODUCTION

Approximately 27 percent of the world's population lacks access to safe drinking water (WHO 2021). Drinking water systems in rural communities are especially prone to violating water safety regulations (Allaire et al. 2018), likely due to limited financial resources, aging infrastructure, and inadequate water quality monitoring. Furthermore, rural residents more frequently rely on private, unregulated wells as their main source of drinking water. Among 43 million Americans relying on unregulated drinking water sources,¹ nearly 2 million lack access to safe drinking water (Darling et al. 2023).

One of the most pressing threats to drinking water quality in rural areas is metal contamination (Bradham et al. 2023). Metal contaminants are persistent, do not degrade, and are consistently ranked among the highest toxicants of concern by the Agency for Toxic Substances and Disease Registry.² When the general public or

Issues surrounding drinking water quality and inadequate monitoring of metal contaminants are particularly relevant in Maine, where 55 percent of residents rely on private wells for drinking water, yet only half of those wells test for arsenic.³ Furthermore, cancer rates are higher in Maine than in the overall US population (MCR 2025). In addition to geological factors, Maine also has among the highest water corrosivity risks in the United States, which can exacerbate vulnerabilities in aging water infrastructure and promote the leaching of lead and other metals from pipes, particularly in older homes (Belitz et al. 2016). However, comprehensive metal contamination monitoring is not standard practice. Barriers to testing and mitigation are multifaceted, spanning geographic challenges (e.g., island communities), socioeconomic constraints (with private wells being the homeowner's responsibility), and psychological factors, including lack of awareness or low perceived vulnerability to drinking water contamination (Flanagan et al. 2018).

In Maine, the public health impacts of contaminated water can be compounded by limited access to

healthcare in rural areas. The Health Resources and Services Administration federally designates many rural communities in Maine as a health professional shortage area (HPSA).⁴ An HPSA designation indicates that an area lacks sufficient access to healthcare professionals to meet local population needs and is used to guide targeted health workforce-building programs. Furthermore, HPSA-designated areas are associated with higher mortality and morbidity (Liu 2007) and correlate with other social determinants of health, including rurality, poverty, and population sparsity (Streeter et al. 2020). These features make it an ideal metric for highlighting areas with unmet healthcare needs. Healthcare shortages can delay diagnosis, treatment, or prevention efforts (Gochfeld and Burger 2011), meaning residents may be less likely to test their water, access education about the health risks related to poor drinking water quality, or obtain medical care for exposure-related illnesses. An overlap of environmental and healthcare disparities may heighten risk for specific populations in Maine, yet these two issues are typically addressed separately.

To better inform state and local policy, we assess the potential public health risks that arise from the intersection of environmental and structural vulnerabilities. We use a dataset of 2,664 private drinking water samples collected between 2016 and 2025 by Maine students involved in a secondary school-based citizen science project called All About Arsenic (Taylor et al. 2024). To evaluate the dual burden of exposure to heavy metal contaminants in areas with limited access to healthcare resources, we analyzed the distribution of metal contaminants in private well samples ($n = 1,887$). By identifying areas of overlapping risk, we aim to provide policymakers, public health professionals, and local leaders with the information needed to ensure equitable access to safe drinking water and health services. Our findings point to potential opportunities for targeted outreach, improved well testing and treatment support, and strategic coordination between environmental and healthcare agencies.

METHODS

Water Sample Collection

The All About Arsenic project has been previously described (Taylor et al. 2024). In brief, samples were collected into 50-milliliter conical tubes by secondary school students or community members in Maine and New Hampshire after running their home tap water for

five minutes. Samples were then sealed with parafilm and returned to the classroom with a completed data-sheet providing details about the sample site, date, time, filtration status, tap location, permissions for research use of data, and sharing information with state agencies, as well as contact information for sending test results. Samples were shipped by the teacher to the Trace Element Analysis Core at Dartmouth College for analysis of toxic metals. Here, we focus on arsenic, barium, beryllium, cadmium, chromium, copper, manganese, lead, antimony, selenium, nickel, and uranium. Some of these analytes are technically metalloids (e.g., arsenic) but are referred to as *metals* throughout this paper. The water quality data were managed in Anecdota, a citizen science data portal developed at MDI Biological Laboratory.⁵

Healthcare Shortage Areas Annotation

Of the 2,664 total samples, we restricted our analysis to private well water samples with complete addresses ($n = 1,887$). For each address, we checked whether the address was located in an HPSA using the Health Resources and Services Administration (HRSA) website.⁶ The HRSA designates HPSAs that lack sufficient access to preventive and primary care to meet the local population's needs and includes classifications for dental health HPSA, mental health HPSA, or primary care HPSA. We also determined whether the address is in a medically underserved area or population, a designation that identifies geographic areas and populations with a shortage of primary care services.

HPSA Scoring

In all HPSA-designated areas, a composite score is calculated to prioritize those with a greater shortage of healthcare providers for intervention and funding. For each primary care HPSA, an additional score, the Maternity Care Target Area (MCTA) score, is calculated using a methodology that specifically considers the availability of maternity care. While the scoring criteria vary across HPSA types, all scores consider the population-to-provider ratio, poverty rates, and travel times to nearest sources of care. Full scoring criteria and maximum associated scores are provided in Table 1.

Statistical Analysis

We summarized the households and information reported in sampling materials using frequency tables. Comparisons between households in each type of HPSA

TABLE 1: **HPSA Scoring Criteria and Associated Maximum Scores**

Criteria	Maximum score
Primary care HPSA score	
Population-to-provider ratio	10
% of population below 100% federal poverty level	5
Infant health index (based on higher score between infant mortality and low birth weight rates)	5
Travel time to nearest source of care outside HPSA	5
Dental health HPSA score	
Population-to-provider ratio	10
% of population below 100% federal poverty level	10
Travel time to nearest source of care outside HPSA	5
Water fluoridation status	1
Maternity target area score	
Population to full-time equivalent maternity care health professional ratio	5
% of population below 200% federal poverty level	5
Travel time to nearest source of care outside HPSA	5
Fertility rate	2
Social vulnerability	2
Maternal health indicator: prepregnancy obesity	1
Maternal health indicator: pre-pregnancy diabetes	1
Maternal health indicator: pre-pregnancy hypertension	1
Maternal health indicator: cigarette smoking	1
Maternal health indicator: prenatal care initiation in the 1st trimester	1
Behavioral health factor	1
Mental health HPSA score	
Population-to-provider ratio	7
% of population below 100% federal poverty level	5
Travel time to nearest source of care outside HPSA	5
Percent of people over age 65	3
Percent of people under age 18	3
Substance abuse prevalence	1
Alcohol abuse prevalence	1

Source: Health Resources and Services Administration Scoring Criteria (2025).

(mental health, primary care, and dental health) and households not in that HPSA were performed for whether the participant reported prior arsenic testing, what the water source was (type of well or a natural spring), whether the sample was filtered, and what kind

of filtration was in place. We assessed differences in the categorical distributions across the potential responses between households in the target HPSA type and those not in the target HPSA type using Pearson’s chi-square tests.

Each private water sample was annotated for whether the recorded value for that metal exceeded the US Environmental Protection Agency’s (EPA) maximum contaminant level. Using a Fisher’s exact test, we first determined whether there was a difference in the rates of water samples with exceedances between households located in any HPSA and households not located in an HPSA. We next examined the count of exceedances, treating each metal with a maximum contaminant level as a unique event, and compared the distribution of samples across three categories: one metal exceeding, two metals exceeding, and three or more metals exceeding the maximum contaminant levels.

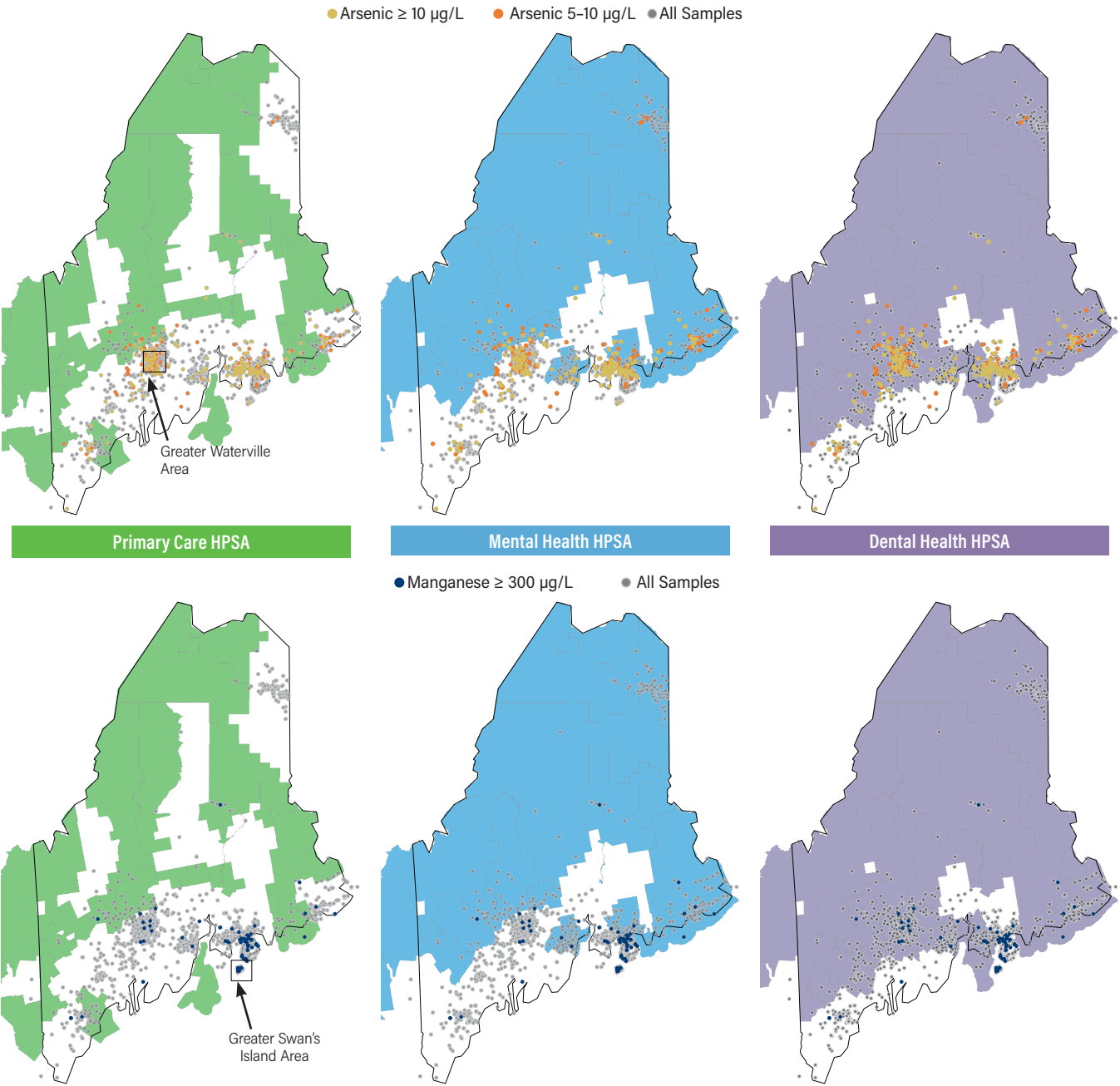
We calculated the fraction of households with a test result meeting or exceeding the maximum contaminant level for each combination of metal and HPSA type by comparing the collection of all households in each HPSA and the households not in an HPSA. Importantly, because some households are located in multiple HPSA types, households are duplicated in these comparisons, and these comparisons should therefore be interpreted as summarizing the trends of households within HPSAs relative to non-HPSA locations rather than comparisons between HPSAs. Finally, we assessed the association between HPSA scores and metal concentrations using Spearman’s rank correlation coefficients, with p-values corrected via the Bonferroni adjustment for the number of assessed metals. Correlation analyses revealed no significant associations with dental or primary care access scores, but we report significant positive correlations between mental health and maternal care health access scores.

RESULTS

HPSA Coverage

Most of the 1,887 private water samples analyzed were HPSAs, while 124 (6.5 percent) were in areas with no HPSA designations (Figure 1).⁷ The most common type of HPSA was dental health (948 households), followed by medically underserved area/population (MUA/P) (955 households), mental health (564 households), and primary care (139 households). In total, 64.6 percent of households fell into one HPSA,

FIGURE 1: All About Arsenic Sample Locations



Notes: (n = 2,664, including the 1,887 private well water samples included in HPSA analyses), color-coded by exceedances of arsenic (top) and manganese (bottom). Panels show all sample locations inside and outside of shaded regions showing HPSA areas for primary care (left), mental health (center), and dental health (right).

while 29 percent fell into two or more, and 3 percent fell into all four types of HPSAs we evaluated.

Infrastructure and Knowledge Gaps in HPSAs

There were differences in the self-reported infrastructure associated with drinking water, including well types, filtration methods, and historical testing results. Across the dental, mental health, and primary care HPSAs, significant differences were observed in the distributions of samples by drinking water source type (Table 2). Across all HPSA types, there were higher numbers of drinking water samples from dug wells in HPSAs compared to samples not from HPSA (Table 2). Dug wells are often found at older homes, so this may

reflect differences in the local infrastructure and its age, but because they are shallower than driven and drilled wells and lack continuous casings, they are prone to multiple types of contamination (Lee and Murphy 2020). Additionally, there were differences in the presence of filtration systems applied to the water samples, with results indicating there were higher percentages of households with no filtration in HPSAs compared to households not in HPSAs. Further, in mental health and primary care HPSAs, the percentage of households not reporting a filtration system exceeded 50 percent.

Importantly, individuals in our dataset often reported that they did not know their drinking water source or whether a filtration system was installed in their

TABLE 2: Participant Characteristics by Health Professional Shortage Area Designation

Characteristic	n	Dental health			Mental health HPSA			Primary care HPSA		
		In n=948 (%)	Not in n=939 (%)	p-value	In n=564 (%)	Not in n=1323 (%)	p-value	In n=139 (%)	Not in n=1748 (%)	p-value
Previous arsenic test	1880			<.001			<.001			<.001
I don't know		243 (26%)	214 (23%)		114 (20%)	343 (26%)		20 (14%)	437 (25%)	
No		343 (36%)	240 (26%)		207 (37%)	376 (29%)		66 (47%)	517 (30%)	
Yes		361 (38%)	479 (51%)		242 (43%)	598 (45%)		53 (38%)	787 (45%)	
Was the sample filtered	1885			<.001			<.001			.5
I don't know		145 (15%)	93 (9.9%)		57 (10%)	181 (14%)		20 (14%)	218 (12%)	
No		552 (58%)	486 (52%)		341 (60%)	697 (53%)		80 (58%)	958 (55%)	
Yes		251 (26%)	358 (38%)		166 (29%)	443 (34%)		39 (28%)	570 (33%)	
Drinking water source	1880			<.001			<.001			<.001
Drilled well		576 (61%)	717 (77%)		403 (71%)	890 (68%)		85 (61%)	1208 (69%)	
Driven well		21 (2.2%)	17 (1.8%)		8 (1.4%)	30 (2.3%)		4 (2.9%)	34 (2.0%)	
Dug well		61 (6.4%)	31 (3.3%)		40 (7.1%)	52 (4.0%)		17 (12%)	75 (4.3%)	
I don't know		266 (28%)	150 (16%)		92 (16%)	324 (25%)		27 (19%)	389 (22%)	
Natural spring		2 (0.2%)	0 (0%)		2 (0.4%)	0 (0%)		0 (0%)	2 (0.1%)	
Other		21 (2.2%)	18 (1.9%)		19 (3.4%)	20 (1.5%)		6 (4.3%)	33 (1.9%)	
Type of filtration system	1839			<.001			<.001			.2
I don't know		208(22%)	108 (12%)		73 (13%)	243 (19%)		21 (15%)	295 (17%)	
No filter		450 (48%)	382 (42%)		297 (53%)	535 (42%)		72 (52%)	760 (45%)	
Other		23 (2.5%)	48 (5.3%)		17 (3.0%)	54 (4.2%)		7 (5.0%)	64 (3.8%)	
Sink-mounted filter		31 (3.3%)	26 (2.9%)		17 (3.0%)	40 (3.1%)		7 (5.0%)	50 (3.2%)	
Water pitcher or refrigerator		33 (3.5%)	23 (2.5%)		15 (2.7%)	41 (3.2%)		2 (1.4%)	54 (3.2%)	
Whole-household filter		188 (20%)	319 (35%)		140 (25%)	367 (29%)		30 (22%)	477 (28%)	

Note: Compared to households located outside the target HPSA. Counts and percentages are shown for each characteristic by category, with p-values indicating comparisons between samples collected inside vs outside the target HPSA region. Sample sizes vary by characteristic based on the number of participants who provided that information.

TABLE 3: **Exceedance Counts among Households in Designated HPSAs or MUA/Ps**

	In any designated HPSA or MUA/P (n=1,763)	Non-HPSA (n=124)	p-value
Any exceedance	254 (14.4%)	21 (16.9%)	0.8
# of exceedance			<.001
1	234 (13.3%)	19 (15.3%)	
2	15 (0.8%)	2 (1.6%)	
≥3	5 (0.2%) One household with 5 unique metal overages	0 (0%)	

Note: Compared to non-HPSA households, with p-values derived from Fisher's exact test. This table only includes exceedances of maximum contaminant levels and action levels set by the US Environmental Protection Agency (see Table 4), meaning it does not include exceedances for the health advisory levels of manganese and nickel, despite their inclusion in Table 4.

household. While the percentage of participants reporting this was not higher in HPSA-designated households compared to non-HPSA-designated households, the prevalence of this result in both areas indicates that Maine residents need a better understanding of the source of their drinking water and its current status. The lack of previous arsenic testing intensifies this need in HPSAs, as a higher proportion of our participants in all three HPSA types report no previous arsenic testing compared to participants not in these HPSAs. These households comprise nearly half of households in primary care HPSAs (47 percent), and more than a third in dental (36 percent) and mental health (37 percent) HPSAs.

Heavy Metal Exceedances in Designated Health Professional Shortage Areas

The EPA has established maximum contaminant, health advisory, and action levels for several of the metals studied here (Table 4, see caption). Across all our samples, 254 households in HPSAs exceeded at least one metal level, compared to 21 in non-HPSAs (Table 3). Across all surveyed households and regions, exceedances of arsenic were observed in 9.7 percent of samples (183/1887), uranium in 2.9 percent (54/1853), lead in 1.5 percent (32/1887), and copper in 24 samples (Table 4).

While the fraction of households with any exceedance did not differ significantly between HPSA and non-HPSA regions ($p = .82$), there were significant differences in the distribution of samples across the spectrum of number of exceedances. In particular, there were five

households with more than three metals detected at levels over the EPA maximum contaminant level located in an HPSA, and one of these had five metals exceeding the recommended limits. These results suggest that households in HPSAs may be more susceptible to multiple concurrent contaminant exceedances and complex metal mixtures than households not in HPSAs.

Arsenic

The EPA designates a maximum contaminant level of 10 parts per billion for arsenic with a suggested goal of 0 parts per billion; Maine uses the 10 parts per billion standard in regulating arsenic in public water systems. In our data set, we detected levels exceeding 10 parts per billion for all regions. However, they were highest in dental health HPSA regions, where 11 percent (108/948) of the surveyed households exceeded the maximum contaminant level, and the maximum recorded arsenic level is more than 10 times the maximum contaminant level, at 185.1 parts per billion. Approximately 10 percent of the samples from mental health and primary care shortage areas exceeded the maximum contaminant level, with levels up to 717.9 parts per billion in the mental health HPSA areas.

Uranium

For uranium, we found levels exceeding the EPA maximum contaminant level of 30 parts per billion across all HPSAs though at lower frequencies than arsenic. Primary care HPSAs had the highest exceedance rate for uranium, with 7.9 percent of the households exceeding the maximum contaminant level and concentrations of up to 329 parts per billion, which is more than 10 times the maximum contaminant level. While the percentages of households exceeding the maximum contaminant level in dental health (1.9 percent), mental health (1.6 percent), and MUA/P (2.5 percent) are lower than the rates in non-designated areas (4.9 percent), they still represent a substantial number of households.

Lead and copper

Lead exceedances were present across all categories. The maximum contaminant level goal for lead is zero, because of its serious affect on physical and mental development in children and health impacts on adults. Primary care HPSAs had the highest exceedance rate at 2.9 percent, followed by mental health HPSAs at 2.3 percent, and dental health HPSAs at 1.7 percent. While non-HPSA areas had comparable frequencies at 2.4 percent,

TABLE 4: **Samples Exceeding EPA Maximum Contaminant Level (MCL), Action Level, or Health Advisory Level across HPSAs and MUA/P**

Metal	MCL	Dental health HPSA (n=948)		Mental health HPSA (n=564)		Primary care HPSA (n=139)		Non-HPSA (n=124)		MUA/P(n=955)	
		% and (#)	Max. (ppb)	% and (#)	Max. (ppb)	% and (#)	Max. (ppb)	% and (#)	Max. (ppb)	% and (#)	Max. (ppb)
Arsenic	10	11.4% (108)	185.1	10.6% (60)	717.9	10.8% (15)	34.4	9.9% (12)	135.1	8.8% (84)	185.1
Barium*	2000	0% (0/737)	363	0.2% (1/490)	2438.2	0% (0/110)	363.8	0% (0/111)	103.3	0% (0/862)	363.8
Beryllium	4	0.1% (1)	6.9	0.4% (2)	35.4	0% (0)	1.1	0% (0)	1.5	0.1% (1)	6.9
Cadmium	5	0.2% (2)	9.8	0.4% (2)	9.8	0% (0)	0.4	0% (0)	0.2	0.1% (2)	9.8
Chromium	100	0% (0)	12.3	0% (0)	4.6	0% (0)	3.0	0% (0)	3.2	0% (0)	4.7
Copper	1300†	1.5% (14)	7006.2	2.1% (12)	7006.2	0.7% (1)	6729.8	1.6% (2)	1760.8	1.7% (16)	7381.7
Manganese	300‡	2.1% (20)	1390.1	3.0% (17)	3180.4	2.2% (3)	886.9	7.3% (9)	4326.3	4.1% (39)	1666.8
	1000§	0.3% (3)	1390.1	1.1% (6)	3180.4	0% (0)	886.9	0.8% (1)	4326.3	0.7% (7)	1666.8
Lead	10†	1.7% (16)	2314.8	2.3% (13)	2314.8	2.9% (4)	2220.2	2.2% (3)	16.9	1.6% (15)	2314.8
Antimony	6	0.1% (1)	20.8	0.4% (2)	24.8	0.7% (1)	6.3	0% (0)	0.5	0.1% (1)	8.4
Selenium*	50	0% (0/947)	3.4	0% (0/563)	3.4	0% (0/139)	2.3	0% (0/124)	0.3	0% (0/954)	3.4
Nickel	100‡	0.3% (3)	475.7	0.4% (2)	130.9	0% (0)	36.9	0% (0)	12.4	0.4% (4)	198.7
Uranium*	30	1.9% (18/948)	139.3	1.6% (9/560)	139.3	7.9% (11/139)	329.0	4.9% (6/122)	737.2	2.5% (23/927)	162.9

* indicates contaminants not tested in all 1,887 samples, so n is presented as n/total n for those metals; † action level; ‡ lifetime health advisory level (for infants, the acute exposure level of manganese); § Adult and child 10-day health advisory level of manganese

Note: Action level for lead and copper or health advisory level for nickel and copper. Sample sizes are given parenthetically in the column headers for each group and do not sum to 1,887 because samples were duplicated across all HPSA types. Values in each cell represent the percentage of samples above the maximum contaminant levels (with count in parentheses) along with the maximum concentration detected for that group. Metals not tested across the whole dataset include barium (tested in 1,589/1,887 samples), uranium (tested in 1,853/1,887 samples), and selenium (tested in 1,886/1,887), and percentages for these are reported as n / total tested n for that metal and are reported as such in the table. Chromium, antimony, beryllium, barium, and nickel have few exceedences both inside and outside of HPSAs.

the highest concentration in non-HPSAs was only 16.9 parts per billion. In contrast, the maximum lead concentrations in HPSAs exceed 2,000 parts per billion, more than 200 times the EPA maximum contaminant level, highlighting the potential for extreme acute exposure in these communities. In our dataset, copper exceedences were observed across all health professional shortage areas and medically underserved areas, but at relatively low frequencies, ranging from 0.7 percent in primary care HPSAs to a maximum of 2.1 percent in mental health HPSAs.

Manganese

At the 300 parts per billion threshold, 7.3 percent of households not in HPSAs exceed the threshold, which outpaces the rates of 2–4 percent in HPSAs. However, this still represents an important group of households that may need targeted information during the pre- and antenatal periods because of the elevated risks of using high-manganese water to prepare infant formula. Further, longtime

residents of these households need to be tested to ensure there are no long-term health impacts at this exposure level. A threshold of 1000 parts per billion, where exposure should be limited to under 10 days for all ages, has been established, yet some households in our study had concentrations exceeding this threshold, including some that exceed this level by three to four times. In mental health HPSAs, 1.1 percent of sampled households exceeded this threshold, with a maximum level of 3,190 parts per billion. The high concentrations observed in some areas raise concerns about chronic exposure and warrant further investigation and potential mitigation efforts.

Other metals

Other metals in our panel that have maximum contaminant levels, action levels, or health advisory limits because of adverse health outcomes include antimony, cadmium, beryllium, barium, and nickel. We did not detect substantial exceedance levels for these contaminants compared to those discussed in more detail

previously, but we did find five exceedances for antimony (0.2 percent), two for cadmium (0.1 percent), three for beryllium (0.1 percent), one for barium (0.1 percent), and seven exceedances of the lifetime health advisory value for nickel. These select households with exceedance values for more rare contaminants highlight the need for continued monitoring and adequate mitigation support for certain regions or individual households.

HPSA Intensity Scores Correlate with Exposures for Key Contaminants

Across our HPSA prioritization scores, we recover positive correlations between the arsenic concentrations and all HPSA types. In this case, a positive correlation indicates that as prioritization scores increase (indicating a more critical shortage), concentrations of metals in sampled wells also increase. Additionally, we find positive correlations between mental health HPSA prioritization scores and antimony, manganese, and uranium concentrations, as well as between dental health HPSA prioritization scores and antimony and uranium concentrations. Together, these associations indicate that in areas with the highest unmet healthcare needs, there are elevated exposure burdens, and potential health concerns are at their highest.⁸

DISCUSSION

Our study highlights an overlap of increased well water contamination with structural healthcare vulnerabilities in rural Maine. The majority (93.4 percent) of our sampled households were in HPSAs. A number of our samples also exceeded US EPA maximum contaminant levels. We detected exceedances of the maximum contaminant level for six of the metals, and additional exceedances of the health advisory levels and action levels for 4 others. While the exceedance rates for any one of the metals we tested were similar between HPSA and non-HPSA households, multiple-metal exceedances were disproportionately concentrated in HPSAs. We identified HPSA households with up to five unique metals at high exceedance levels, as well as households with extreme outliers across multiple metals. Alarming, we find that HPSA scores were positively associated with contaminant levels, such as arsenic and mental health care shortages, or arsenic and maternal care shortages. These associations suggest that exposure risks and limited access to healthcare can

compound health risks among some of the most vulnerable communities in Maine.

Many HPSA households in our dataset reported no filtration systems or uncertainty about their water source, and prior arsenic testing was markedly lower in shortage areas. These gaps are consistent with barriers described in previous rural water studies, including geographic isolation, cost of testing, lack of public awareness, and the absence of mandatory private well regulation. The convergence of these environmental and social factors in Maine parallels patterns seen nationally in the United States, where exceedances of regulatory guidelines cluster in disadvantaged rural communities (Allaire et al. 2018). Drinking water contamination is therefore not solely an environmental problem but is amplified by structural vulnerabilities in healthcare access, infrastructure, and public health outreach.

Limitations

Part of the utility of the All About Arsenic dataset is that we are specifically evaluating samples collected by secondary school students, this approach helps us specifically understand the risk profile for families with children, which often includes siblings of various ages or multigenerational family members. By centering households with children, our dataset captures information about a high-risk population subset where effective mitigation and early intervention may have a disproportionate impact on Maine public health. However, this means that our dataset, as a school-based initiative, is not a random sampling, and it may limit the direct generalization to Maine households without children or communities not reached by participating schools. Within Maine, this means we likely do not have access to older adult cohorts, a group that is also at elevated risk of contaminant exposure and at increased vulnerability to limited healthcare access. Because the households engaged in the All About Arsenic program are located around participating schools, we are also geographically limited and have uneven sampling distribution across HPSA subtypes and across HPSA intensity scores. This limitation reduces our statistical power for certain subgroup comparisons and increases the risk of unstable estimates about the prevalence of rare exceedances. Despite these limitations, the extreme concentrations observed for certain contaminants, the multimetal exceedances, and clusters of high-contamination households in HPSA regions represent both acute and chronic health hazards

and justify targeted testing, remediation, and healthcare outreach.

Health Implications for Maine

Dental health

Nearly half our participants live in dental health HPSAs, and the overlap between dental care shortages and well water contamination reveals an overlooked public health gap. In dental HPSAs, fewer households test their water, filtration systems are less common, and uncertainty about well type is high, which is a missed frontline of surveillance. Dentists and dental hygienists are well-positioned to identify early signs of exposure, such as enamel defects, unexplained copper staining, aggressive tooth decay linked to lead, or periodontal inflammation associated with arsenic. However, these same communities face some of the most limited access to dental care; in fact, the concentrations of arsenic, antimony, and uranium are significantly associated with the prioritization score, indicating that communities most in need of dental care often have highest burden of exposure to these metals. The absence of regular dental visits delays recognition and intervention, allowing health effects to compound. Untreated periodontal disease, for example, amplifies systemic inflammation and increases cardio-metabolic risk, creating a cycle of vulnerability linking environmental exposure to chronic disease (Zhou et al. 2023).

Mental health

Approximately 30 percent of our samples are from a mental health HPSA. Our data revealed several metals were elevated in mental health HPSAs, including both higher rates of maximum contaminant level exceedances and positive correlations with HPSA intensity scores. Several (including manganese, copper, lead, arsenic, antimony, and uranium) have documented associations with adverse mental health outcomes. Arsenic showed the strongest correlation with HPSA intensity scores, and 10.6 percent of our samples exceeded the federal maximum contaminant level. Chronic arsenic exposure has been linked to inflammation and oxidative stress in the brain, which can contribute to mood disorders and depressive symptoms (Tyler and Allan 2014). Additionally, lead exposure contributes to cognitive decline, depression, and behavioral disorders (van den Bosch and Meyer-Lindenberg 2019). While we observed a relatively low percentage of lead exceedances (2.3 percent), we also detected a maximum lead concentration of 2,314

parts per billion, over 200 times the federal action level, and found a significant correlation between lead concentration and HPSA intensity score. Further, antimony exposure is associated with depressive and anxiety symptoms, particularly among women, and risks may be elevated when it co-occurs with other metals (Zhang et al. 2022). In addition to direct impacts, exposure to these metals may indirectly influence mental health by contributing to physical conditions, such as endocrine disruption, dermatologic effects like alopecia, or chronic inflammatory states. These findings suggest that populations in mental health HPSAs may face a dual burden of limited access to care and increased environmental exposure to metals implicated in adverse mental health outcomes.

Cancer

Maine presents a concerning intersection of environmental metal exposures, healthcare shortages, and elevated cancer incidence. While we do not focus on specialized care like oncology, reduced access to general care can contribute to delayed diagnosis in rural areas (Campbell et al. 2001). Importantly, there is evidence that access to oncology care is limited in Maine, as the number of radiation oncologists per capita is well below the national average (Bates et al. 2020), and many residents must travel to surrounding states for cancer care (Moen et al. 2025). The scale of the cancer burden in Maine is striking, as Maine has an age-adjusted incidence well above the national average (MCR 2025). Further, Maine has the highest incidence in the country of childhood cancers. Among specific cancer types, Maine has the highest age-adjusted incidence of bladder cancer in the country and has among the highest national rates of oral cavity and pharynx (second), esophagus (second), lung (third), brain and other nervous system (fourth), uterus (fifth), and melanoma (eighth) cancers. The development and progression of many of these types of cancers can be related to metal exposures via drinking water. For example, exposure to arsenic has been associated with bladder cancer (Baris et al. 2016) and lead has been associated with multiple cancer types (Vagnoni et al. 2024). Furthermore, while the cancer associations with uranium remain underexplored, there are tentative associations with a number of cancer types (Alimam and Auvinen 2025). Smoking status further amplifies health risks associated with metal exposure, and smoking prevalence in Maine remains above the national average (TPCAC 2022). Given that we detect exceedances of

these metals in HPSAs, our work highlights the need for further monitoring and epidemiological studies to more closely examine this potential link to cancer rates in Maine and to identify intervention targets to reduce cancer morbidity and mortality across the state.

Subgroups at Increased Risks

Certain populations in Maine face disproportionately high risks from well water contamination and may require targeted monitoring, surveillance, and outreach to prevent adverse health outcomes.

Pregnant people, infants, and children

Pregnancy, infancy, and early childhood represent critical windows of vulnerability to adverse health effects of metal exposures. Physiological changes during pregnancy can increase the mobilization and transfer of metals to the developing fetus and can modify risks for pregnancy-associated conditions like gestational diabetes and are associated with adverse pregnancy outcomes like low birth weight (Zhong et al. 2019). Moreover, the All About Arsenic dataset evaluates samples collected by secondary school students, which helps us specifically understand the risk profile for families with children. Children are disproportionately vulnerable to heavy metal toxicity. Children's neurological, immune, and organ systems are still developing, making them more susceptible to irreversible damage (Rauh and Margolis 2016). Early-life exposures can impact neurodevelopment in children (Tolins et al. 2014). Further, by definition, lifetime exposure begins in early life. Early exposure to metals like arsenic, lead, manganese, and uranium is linked to long-term adverse health effects (Landrigan and Garg 2002). In Maine specifically, a previous study showed that children exposed to arsenic levels as low as 5 parts per billion had adverse neurodevelopmental outcomes, emphasizing that even moderate exposure below the maximum contaminant level can carry health risks for young children (Wasserman et al. 2014). By centering on households with children, our dataset captures information about a high-risk population subset for which effective mitigation and early intervention may have a disproportionate impact on public health. While Maine law has required blood lead testing for all one- and two-year-olds since June 2019, there is no requirement to test private well water for lead, despite mounting evidence suggesting that contaminated drinking water is a potential exposure pathway. Our findings of elevated lead levels in HPSAs indicate that routine well testing should be

integrated into pediatric care, consistent with recommendations from Woolf et al. (2023).

Older adults

Maine has one of the largest proportions of older adults in the country. Older adult populations are at elevated risk for contaminant exposures (Jafri 2011) and can be more susceptible to the cumulative toxic effects of metals like arsenic, lead, and uranium (Zheng et al. 2024). Because the households engaged in the school-based All About Arsenic program are located around participating schools, the generalization of our findings to Maine households without children, communities not reached by participating schools, or older adult populations may be limited. However, the extreme concentrations observed for specific contaminants and clusters of high-contamination households in HPSA regions justifies targeted testing, remediation, and healthcare outreach to Maine's vulnerable older adult population. Limited mobility, fixed incomes, and reduced access to transportation or technology act as barrier to testing and mitigation in this group. Therefore, integrating well water testing into senior health programs and expanding outreach to this population is a critical step in reducing preventable morbidity and mortality.

Outer islands

Households on Maine's outer islands may be a key area for rural health initiatives. Most outer island samples were collected on Swan's Island because its school is involved in All About Arsenic. These households exhibit particularly high manganese concentrations, raising concerns given the neurotoxic effects of manganese, especially in children. The geography of the outer island communities presents challenges to healthcare access and drinking water quality due to their remoteness and unique geology and the impacts of sea-level rise on groundwater. Additionally, while travel distance to healthcare professionals from the outer islands may not be any farther than from other remote areas of Maine, there are complications, including boat and ferry availability, marine conditions, and mainland transport options. This geographic barrier may delay testing, diagnosis, and intervention, leaving these households at an elevated risk of drinking water metal exposure, even though the Maine Seacoast Mission provides essential services and projects, such as the ongoing Healthy Water Healthy Aging program (MSM 2023). Islands need more targeted outreach to increase well water testing, to understand

how residents access drinking water, and to mitigate exposure risk to support communities.

Emerging concerns of multiple exposures and PFAS

Although the analyses we present here consider each metal independently, our work provides a strong foundation for future, more complex analyses of multi-metal mixtures. Adverse effects of metals can be compounded or modified by coexposure to other metals (Babich et al. 2021). Applying mixture modeling into future work could also be extended to other environmental contaminants, such as per- and polyfluoroalkyl substances (PFAS), providing a more comprehensive understanding of combined exposure risks.

With the passage of SP 64 (Resolve, To Protect Consumers of Public Drinking Water by Establishing Maximum Contaminant Levels for Certain Substances and Contaminants), the Maine Legislature required schools and daycares to sample drinking water for PFAS. Through this sampling initiative, it was found that the drinking water in many rural Maine schools has measurable levels of PFAS, with some schools exceeding the 20 nanograms/liter total limit established for six regulated PFAS contaminants. Recent analysis of data from the Maine Drinking Water Program found that 18 percent of Maine schools exceeded the state standard. PFAS contamination of drinking water in Maine schools can also affect neighboring wells (Moran Sosa et al. 2024). The combined health implications of metals or PFAS exposure, coupled with the locations of schools and communities in HPSAs, are of additional concern.

RECOMMENDATIONS AND POLICY NEEDS

In light of our project's student drinking water data, analysis of sample locations relative to HPSAs, and identification of areas of rural Maine with both high exposure risk and health professional access deficits, we have framed the following recommendations and policy needs.

Require and Support Increased Private Well Testing

We recommend a state-level mandate for private well water testing, especially in HPSA-designated rural areas with high reliance on private well water. Mandates could take the form of private drinking water regulation. For example, a real estate transaction requirement for testing drinking water for metals and other contaminants at the time of home sale or construction of new homes is an approach that has been successful in New Jersey,

where the Private Well Testing Act requires arsenic testing during real estate transactions and has increased testing (Flanagan et al. 2018). Additionally, funding for remediation, filtration, and water testing in medically underserved areas should be prioritized. Progress has been made on this front with the passage of LD 1891—An Act to Continue Supporting Safe Drinking Water for Maine Families—in May 2022. The legislation has enabled the Maine State Housing Authority to provide remediation grants to single-family homeowners or landlords with contaminated private wells; however, it is tied solely to income and does not fully account for health risks. Critically, while mitigation and treatment are effective in reducing arsenic exposure, a study of treatment systems in rural Maine households found that half the systems successfully reduced arsenic levels below 1 parts per billion, while 19 percent failed (Yang et al. 2020). Follow-up education and testing to ensure successful reductions in metal concentrations are needed after mitigation activities to ensure that Maine residents continue to have access to safe drinking water.

Prioritize Rural Areas

Pairing environmental monitoring initiatives with Maine rural health clinics by providing targeted information to healthcare workers and patients could have a significant impact on public health in the state. This was previously demonstrated in a study of pediatric preventive care (Murray et al. 2020). We further recommend considering toxic exposure risks from drinking water in decisions about hospital and clinic closures in rural areas. Our research indicates that areas with gaps in healthcare access frequently experience drinking water contamination. The closure of the hospital in Waterville and the maternity care ward on Mount Desert Island highlight how the landscape of access to care can change quickly in Maine, leaving at-risk communities without sufficient support. Similarly, integrating water quality concerns and the locations of drinking water contamination into Maine's rural healthcare expansion plans should be prioritized, including recruiting healthcare professionals to the state, increasing telehealth access, and other approaches to improving the quality and access of healthcare in rural environments.

Education and Health Promotion

Our work highlights that residents in HPSAs have limited information about their well type and previous testing. By addressing education gaps, residents become

aware of their water source, the last test date, and the associated exposure risks. Drinking water education in public schools and across all levels of society is particularly important in states like Maine, which rely heavily on unregulated private drinking water. In addition, education of healthcare professionals about drinking water quality is important but often overlooked. Healthcare professionals outside Maine may not be aware of the risks of toxic metal exposure for rural Mainers. Even professionals from Maine may not be aware of emerging concerns about less common metals, metal mixtures, or PFAS contamination, as we are just beginning to learn about the extent of these issues. It may be possible to use existing public health infrastructure in rural Maine to raise awareness of drinking water contamination and promote and support testing and remediation

CONCLUSIONS

The potential public health risks arising from the intersection of environmental and structural vulnerabilities and other rural issues, especially given elevated cancer incidence in Maine, highlight the importance of integrated analyses and the need for ongoing water quality monitoring throughout the state. The list of recommendations and policy needs is long and complex. Currently, Maine has a piecemeal approach; some testing is underway, and some households are being mitigated. Additionally, some families are safer than before due to education and outreach efforts from our program and from some municipalities and state agencies. Yet, each year, dozens of households are still found to have elevated levels of one or more toxic metals; in most cases, families have no idea that these metals pose a health issue or that filtration options exist. The data we present here highlight the importance of screening for multiple metals. Our findings also highlight the implications of other variables, such as household location within HPSAs, that can magnify health risks associated with arsenic, uranium, lead, and manganese, and potentially other toxic contaminants like PFAS. Beyond the need for screening is the need for a comprehensive approach to mitigation and ongoing maintenance of filtration systems, the expansion of public water systems into rural areas or shared community systems that can be maintained at the neighborhood or municipal level.

ACKNOWLEDGMENTS

This work was supported by US Environmental Protection Agency (EPA) NE-83592001, the National Institute of General Medical Sciences (NIGMS) of the National Institutes of Health (NIH) with a Science Education Partnership Award (SEPA) under grants R25GM129796 and 3R25GM129796-02S1, the National Institute of Nursing (NINR) of the NIH with a SEPA under grant 1R25NR021077, the New Hampshire INBRE through an IDeA from the NIGMS of the NIH under grant P20GM103506, the Maine INBRE and the Center for Biomedical Research Excellence (COBRE) through an IDeA from the NIGMS of the NIH under grants P20GM103423 and P20GM104318, the National Cancer Institute Cancer Center Support Grant (P30CA023108), a Prouty Pilot Grant from Friends of Dartmouth Cancer Center, a National Institute of Environmental Health Sciences Award under grant P42ES007373. Funding for PFAS initiatives came from grant P30 ES00002 from the National Institute for Environmental Health Sciences to the Harvard Chan NIEHS Center and the Shultz Fund at MDI Biological Laboratory.

NOTES

- 1 "Private Drinking Water Wells, US EPA, <https://www.epa.gov/privatewells>
- 2 "Substance Priority List," Agency for Toxic Substances and Disease Registry, <https://www.atsdr.cdc.gov/programs/substance-priority-list.html>
- 3 "Private Well Water," Maine Tracking Network, Maine CDC, <https://data.mainepublichealth.gov/tracking/private-wells>
- 4 "HPSA Find," Health Resources and Services Administration (HRSA) Data Warehouse, <https://data.hrsa.gov/topics/health-workforce/shortage-areas/hpsa-find>
- 5 "All About Arsenic," Anecdotal, <https://www.anecdotal.org/projects/view/299>
- 6 <https://data.hrsa.gov/topics/health-workforce/shortage-areas/hpsa-find>
- 7 An additional figure is available as supplemental online information: <https://doi.org/10.53558/znox3244>.
- 8 Dental health $P_{\text{adjusted}} = 4.1 \times 10^{-7}$; mental health $P_{\text{adjusted}} = 1.7 \times 10^{-13}$; primary care $P_{\text{adjusted}} = 0.006$; maternity care $P_{\text{adjusted}} = 0.04$; antimony ($P_{\text{adjusted},12} = 2.1 \times 10^{-8}$), manganese ($P_{\text{adjusted},12} = 0.0002$), and uranium ($P_{\text{adjusted},12} = 6.6 \times 10^{-4}$) concentrations, as well as between dental health HPSA prioritization scores and antimony ($P_{\text{adjusted},12} = 2.1 \times 10^{-8}$) and uranium ($P_{\text{adjusted},12} = 1.4 \times 10^{-7}$) concentrations. We do recover a significant negative correlation between chromium and dental HPSA prioritization scores ($P_{\text{adjusted},12} = 0.001$)

REFERENCES

- Alimam, Wafa, and Anssi Auvinen. 2025. "Cancer Risk Due to Ingestion of Naturally Occurring Radionuclides through Drinking Water: A Systematic Review." *Science of The Total Environment* 968:178849. <https://doi.org/10.1016/j.scitotenv.2025.178849>.
- Allaire, Maura, Haowei Wu, and Upmanu Lall. 2018. "National Trends in Drinking Water Quality Violations." *Proceedings of the National Academy of Sciences of the United States of America* 115(9): 2078–2083. <https://doi.org/10.1073/pnas.1719805115>.
- Babich, Remy, Emily Craig, Abigail Muscat, Jane Disney, Anna Farrell, Linda Silka, and Nishad Jayasundar. 2021. "Defining Drinking Water Metal Contaminant Mixture Risk by Coupling Zebrafish Behavioral

- Analysis with Citizen Science." *Scientific Reports* 11(1): 1. <https://doi.org/10.1038/s41598-021-96244-4>.
- Baris, Dalsu, Richard Waddell, Laura E. Beane Freeman, Molly Schwenn, Joanne S. Colt, Joseph D. Ayotte, Mary H. Ward, et al. 2016. "Elevated Bladder Cancer in Northern New England: The Role of Drinking Water and Arsenic." *JNCI: Journal of the National Cancer Institute* 108(9): djw099. <https://doi.org/10.1093/jnci/djw099>.
- Bates, James E., Akash D. Parekh, Mudit Chowdhary, and Robert J. Amdur. 2020. "Geographic Distribution of Radiation Oncologists in the United States." *Practical Radiation Oncology* 10(6): e436–443. <https://doi.org/10.1016/j.prro.2020.04.008>.
- Belitz, Kenneth, Bryant C. Jurgens, and Tyler D. Johnson. 2016. *Potential Corrosivity of Untreated Groundwater in the United States*. Scientific Investigations Report 2016–5092. US Geological Survey. <https://doi.org/10.3133/sir20165092>
- Bosch, Matilda van den, and Andreas Meyer-Lindenberg. 2019. "Environmental Exposures and Depression: Biological Mechanisms and Epidemiological Evidence." *Annual Review of Public Health* 40:239–259. <https://doi.org/10.1146/annurev-publhealth-040218-044106>.
- Bradham, Karen D., Clay M. Nelson, Tyler D. Sowers, Darren A. Lytle, Jennifer Tully, Michael R. Schock, Kevin Li, et al. 2023. "A National Survey of Lead and Other Metal(Loids) in Residential Drinking Water in the United States." *Journal of Exposure Science & Environmental Epidemiology* 33(2): 160–167. <https://doi.org/10.1038/s41370-022-00461-6>.
- Campbell, N.C., A.M. Elliott, L. Sharp, L.D. Ritchie, J. Cassidy, and J. Little. 2001. "Rural and Urban Differences in Stage at Diagnosis of Colorectal and Lung Cancers." *British Journal of Cancer* 84(7): 910–14. <https://doi.org/10.1054/bjoc.2000.1708>.
- Darling, Amanda, Hannah Patton, Md Rasheduzzaman, Rachel Guevara, Joshua McCray, Leigh-Anne Krometis, and Alasdair Cohen. 2023. "Microbiological and Chemical Drinking Water Contaminants and Associated Health Outcomes in Rural Appalachia, USA: A Systematic Review and Meta-Analysis." *Science of the Total Environment* 892:164036. <https://doi.org/10.1016/j.scitotenv.2023.164036>.
- Flanagan, Sara V., Jessie A. Gleason, Steven E. Spayd, Nicholas A. Procopio, Megan Rockafellow-Baldoni, Stuart Braman, Steven N. Chillrud, and Yan Zheng. 2018. "Health Protective Behavior Following Required Arsenic Testing under the New Jersey Private Well Testing Act." *International Journal of Hygiene and Environmental Health* 221(6): 929–940. <https://doi.org/10.1016/j.ijheh.2018.05.008>.
- Gochfeld, Michael, and Joanna Burger. 2011. "Disproportionate Exposures in Environmental Justice and Other Populations: The Importance of Outliers." *American Journal of Public Health* 101:S53–S63. <https://doi.org/10.2105/AJPH.2011.300121>.
- Jafri, Asma B. 2011. "Aging and Toxins." *Clinics in Geriatric Medicine* 27(4): 609–628. <https://doi.org/10.1016/j.cger.2011.07.007>.
- Landrigan, Philip J., and Anjali Garg. 2002. "Chronic Effects of Toxic Environmental Exposures on Children's Health." *Journal of Toxicology: Clinical Toxicology* 40(4): 449–456. <https://doi.org/10.1081/CLT-120006747>.
- Lee, Debbie, and Heather M. Murphy. 2020. "Private Wells and Rural Health: Groundwater Contaminants of Emerging Concern." *Current Environmental Health Reports* 7(2): 129–139. <https://doi.org/10.1007/s40572-020-00267-4>.
- Liu, Jiexin (Jason). 2007. "Health Professional Shortage and Health Status and Health Care Access." *Journal of Health Care for the Poor and Underserved* 18(3): 590–598.
- MCR (Maine Cancer Registry). 2025. 2025 Maine Cancer Snapshot. Maine Department of Health and Human Services, MCR. <https://www.maine.gov/dhhs/mecdc/data-reports/diseases/chronic-disease/cancer/cancer-registry/cancer-registry-reports>.
- MSM (Maine Seacoast Mission). "Healthy Water, Healthy Aging on Maine's Unbridged Islands," October 21. <https://seacoastmission.org/well-water-testing/>.
- Moen, Erika L., Qianfei Wang, Lingbo Liu, Fahui Wang, Anna N.A. Tosteson, Rebecca E. Smith, Lauren Cowan, and Tracy Onega. 2025. "Cross-State Travel for Cancer Care and Implications for Telehealth Reciprocity." *JAMA Network Open* 8(2): e2461021. <https://doi.org/10.1001/jamanetworkopen.2024.61021>.
- Moran Sosa, Ludwin, Ashley Taylor, Alexis C. Garretson, Ann Backus, Katie Richards, Joel H. Graber, Richard F. Hilliard, and Jane E. Disney. 2024. "Examining Potential PFAS Contamination of Private Wells from a High School in Rural Maine." *Environmental Health Perspectives* 132(12): 127701. <https://doi.org/10.1289/EHP14653>.
- Murray, Carolyn J., Ardis L. Olson, Ellen L. Palmer, Qian Yang, Christopher I. Amos, Deborah J. Johnson, and Margaret R. Karagas. 2020. "Private Well Water Testing Promotion in Pediatric Preventive Care: A Randomized Intervention Study." *Preventive Medicine Reports* 20:101209. <https://doi.org/10.1016/j.pmedr.2020.101209>.
- Rauh, Virginia A., and Amy Margolis. 2016. "Research Review: Environmental Exposures, Neurodevelopment and Child Mental Health – New Paradigms for the Study of Brain and Behavioral Effects." *Journal of Child Psychology and Psychiatry, and Allied Disciplines* 57(7): 775–793. <https://doi.org/10.1111/jcpp.12537>.
- Rehman, Kanwal, Fiza Fatima, Iqra Waheed, and Muhammad Sajid Hamid Akash. 2018. "Prevalence of Exposure of Heavy Metals and Their Impact on Health Consequences." *Journal of Cellular Biochemistry* 119(1): 157–184. <https://doi.org/10.1002/jcb.26234>.
- Sinha, Dona, and Priyanka Prasad. 2020. "Health Effects Inflicted by Chronic Low-Level Arsenic Contamination in Groundwater: A Global Public Health Challenge." *Journal of Applied Toxicology* 40(1): 87–131. <https://doi.org/10.1002/jat.3823>.
- Streeter, Robin A., John E. Snyder, Hayden Kepley, Anne L. Stahl, Tiandong Li, and Michelle M. Washko. 2020. "The Geographic Alignment of Primary Care Health Professional Shortage Areas with Markers for Social Determinants of Health." *PLOS One* 15(4): e0231443. <https://doi.org/10.1371/journal.pone.0231443>.
- Taylor, Ashley, Alexis Garretson, Karen H. Bieluch, Kate L. Buckman, Hannah Lust, Cait Bailey, Anna E. Farrell, et al. 2024. "A Mixed Methods Approach to Understanding the Public Health Impact of a School-Based Citizen Science Program to Reduce Arsenic in Private Well Water." *Environmental Health Perspectives* 132(8): 087006. PMID: PMC11338042.
- TPCAC (Tobacco Prevention and Control Advisory Council). 2022. Tobacco Prevention and Control Advisory Council Report. https://www.maine.gov/dhhs/mecdc/sites/maine.gov/dhhs/mecdc/files/Tobacco_Advisory_Report_2022.pdf.
- Tolins, Molly, Mathuros Ruchirawat, and Philip Landrigan. 2014. "The Developmental Neurotoxicity of Arsenic: Cognitive and Behavioral Consequences of Early Life Exposure." *Annals of Global Health* 80(4): 303–14. <https://doi.org/10.1016/j.aogh.2014.09.005>.
- Tyler, Christina R., and Andrea M. Allan. 2014. "The Effects of Arsenic Exposure on Neurological and Cognitive Dysfunction in Human and

- Rodent Studies: A Review." *Current Environmental Health Reports* 1(2): 132–47. <https://doi.org/10.1007/s40572-014-0012-1>.
- Vagnoni, Giulia, Emma Bortolotti, Saverio Checchi, Calogero Saieva, Giovanna Berti, Chiara Doccioli, and Saverio Caini. 2024. "Lead (Pb) in Biological Samples in Association with Cancer Risk and Mortality: A Systematic Literature Review." *Cancer Epidemiology* 92:102630. <https://doi.org/10.1016/j.canep.2024.102630>.
- Wasserman, Gail A., Xinhua Liu, Nancy J. Lolacono, Jennie Kline, Pam Factor-Litvak, Alexander van Geen, Jacob L. Mey, et al. 2014. "A Cross-Sectional Study of Well Water Arsenic and Child IQ in Maine Schoolchildren." *Environmental Health* 13(1): 23. <https://doi.org/10.1186/1476-069X-13-23>.
- Woolf, Alan D., Bryan D. Stierman, Elizabeth D. Barnett, Lori G. Byron, and Committee on Infectious Diseases Council on Environmental Health and Climate Change. 2023. "Drinking Water From Private Wells and Risks to Children." *Pediatrics* 151(2): e2022060645. <https://doi.org/10.1542/peds.2022-060645>.
- WHO (World Health Organization). 2021. *Progress on Household Drinking Water, Sanitation and Hygiene 2000–2020: Five Years into the SDGs*. WHO. <https://www.who.int/publications/i/item/9789240030848>.
- Yang, Qiang, Hun Bok Jung, Charles W. Culbertson, Robert G. Marvinney, Marc C. Loiselle, Daniel B. Locke, Heidi Cheek, Hilary Thibodeau, and Yan Zheng. 2009. "Spatial Pattern of Groundwater Arsenic Occurrence and Association with Bedrock Geology in Greater Augusta, Maine." *Environmental Science & Technology* 43(8): 2714–2719. <https://doi.org/10.1021/es803141m>.
- Yang, Saiyan, Jun Li, and Yousheng Wu. 2025. "The Association of Lead and Cadmium Exposure with Periodontitis: A Systematic Review and Meta-Analysis." *BMC Oral Health* 25(June): 935. <https://doi.org/10.1186/s12903-025-06195-9>.
- Zhang, Tianhao, Jia Luo, Honghan Ge, Kangyu Hao, Zixuan Wang, and Dongfeng Zhang. 2022. "Relationships between Urinary Antimony Concentrations and Depressive Symptoms in Adults." *Chemosphere* 291:133104. <https://doi.org/10.1016/j.chemosphere.2021.133104>.
- Zheng, Zitian, Huanhuan Luo, and Qingyun Xue. 2024. "The Association of Urinary Heavy Metal Exposure with Frailty Susceptibility and Mortality in Middle-Aged and Older Adults: A Population-Based Study." *Archives of Public Health* 82(1): 44. <https://doi.org/10.1186/s13690-024-01275-8>.
- Zhong, Qi, Yanjie Cui, Huabing Wu, Qingshan Niu, Xuelei Lu, Ling Wang, and Fen Huang. 2019. "Association of Maternal Arsenic Exposure with Birth Size: A Systematic Review and Meta-Analysis." *Environmental Toxicology and Pharmacology* 69:129–136. <https://doi.org/10.1016/j.etap.2019.04.007>.
- Zhou, Shuduo, Wenjing Li, Jun Wan, Yixuan Fu, Hongye Lu, Na Li, Xu Zhang, et al. 2023. "Heavy Metals in Drinking Water and Periodontitis: Evidence from the National Oral Health Survey from China." *BMC Public Health* 23:1706. <https://doi.org/10.1186/s12889-023-16391-3>.

Alexis Garretson is a post-doctoral researcher at the University of Utah and a data specialist with MDI Biological Laboratory's Community Environmental Health Lab. Her research focuses on enabling data reuse and synthesis investigations at the nexus of health and environmental quality research to foster community advocacy for environmental improvement.

Alexandra Duffy is an assistant research professor in the Department of Biological Sciences at North Carolina State University (NCSU) and an affiliate member of the NCSU Global One Health Academy. She integrates ecology, evolution, analytical chemistry, and genetics to elucidate the environmental factors contributing to complex behaviors, diseases, and evolutionary outcomes.

Richard Hilliard is a post-doctoral researcher with the Community Environmental Health Lab, primarily focused on studying PFAS movement in the environment and groundwater supplying private wells, as well as identifying strategies to mitigate PFAS contamination in coastal environments.

Ashley Taylor is a geographic information system specialist affiliated with the Community Environmental Health Lab. Her work entails investigating the spatial visualization and representation of contaminants in drinking water and the natural environment.

Caitlin Oliver-Olsen works at the Community Environmental Health Lab, where she coordinates the NIH Science Education Partnership Award (SEPA) program and manages related scientific research.

Morgan Karns contributed to this project during her time as an Island Institute Fellow. She is currently a graduate student at Virginia Tech, focusing on environmental and experiential education.

Jane Disney is an associate professor of environmental health at MDI Biological Laboratory. She is the founder and director of the Community Environmental Health Laboratory. She works with multiple community partners, identifying and helping to remedy threats to public health and the clean waters of coastal Maine.