

Reducing public exposure to common, harmful well water contaminants through targeted outreach to highly susceptible neighborhoods as a method of increasing the likelihood of testing and treatment of water from private wells

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ABSTRACT

While the Safe Drinking Water Act mandates testing of public water supplies in the USA, private well owners are responsible for testing and treating their own water. A small percentage of well owners perform annual testing as recommended and many never test at all for common and potentially harmful groundwater contaminants. Finding effective ways to inform residents of the risks associated with their private well drinking water and promote the testing and treatment for common contaminants is a challenge faced by federal, state, and local agencies concerned with public health. Targeting residents whose wells are most at risk for having levels of regulated contaminants above the drinking water standard is a potential way to efficiently reach individuals. Results of this study show that individuals who receive specific letters that a contaminant in a neighbor's well had exceeded the maximum contaminant levels for one of five common well water contaminants (arsenic, radon, Gross Alpha, *Escherichia coli*, and nitrates) were more likely to test their well than were individuals who received a general letter about common contaminants in the region. Outreach that reports more localized, specific information on contaminants in well water results in an increased chance of testing when compared with more regional and generalized contaminant information.

Key words | arsenic, drinking water, groundwater quality, health actions, private wells, well water contaminants

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HIGHLIGHTS

- Provides insights into well water testing behaviors and obstacles.
- Informs international efforts to educate the public on well water contaminants, testing and treatment.
- Explores messaging in testing outreach campaigns to reduce well water contaminant exposure.

INTRODUCTION/BACKGROUND

The 1974 Safe Drinking Water Act (SDWA) regulates water quality for more than 148,000 public water systems in the USA to protect public health. These systems are classified

by the U.S. Environmental Protection Agency according to the number of people they serve and whether they serve the same customers year-round or on an occasional basis

(USEPA 2020). Community Water Systems, which may be publicly or privately owned, provide water for human consumption to at least 15 service connections or serve an average of at least 25 people for at least 60 days a year. These supplies are subject to rigorous federal testing requirements and states have the authority to mandate stricter regulations for community systems to meet state standards for water quality. However, the federal SDWA does not regulate private wells, and state and local government requirements for private well water testing are uncommon and inconsistent among states. Thus, private well owners are largely responsible for the safety of their own water.

According to the 2009 American Housing Survey, about 15.8 million homes in the USA are served by a private well (U.S. Census Bureau 2009), and the majority of these households are located in rural areas (Simpson 2004). The U.S. Geological Survey (USGS) reports that more than 20% of 2,100 private domestic wells sampled nationwide from 1991 to 2004 contained at least one contaminant at levels of potential health concern (DeSimone *et al.* 2009). About 13% of New Jersey residents or 1.15 million people get their drinking water from private wells. Of the roughly 300,000 private wells in New Jersey, only 20–25% of them have been tested at least once under New Jersey's 2002 Private Well Testing Act which mandates the testing of domestic wells upon transfer of ownership (NJDEP 2016). This potentially leaves as many as 80% of the remaining wells in the state unmonitored for water quality. Thus, there is a critical need to better inform private well owners of the risks of contaminants exceeding drinking water standards in their well water in ways that will result in health actions including testing and treatment.

In the Upper Raritan Watershed Region (WMA8) of New Jersey, 80% of residents rely on private wells for drinking water (MacDonald & Thomas 2016). Well water contaminants including arsenic, nitrates, total coliform bacteria, lead, volatile organic compounds, and radionuclides are commonly found and pose threats to public health. Table 1 provides an overview of environmental sources, NJ state and federal maximum contaminant levels (MCLs), health impacts, and testing requirements for the five common well water contaminants in this study. Sources of high levels of nitrate and *Escherichia coli* include activities associated with urban, agricultural, and industrial land uses (Squillace

et al. 2002; Swistock & Sharpe 2005; Gonzales 2008; Naylor *et al.* 2018), whereas sources of arsenic, radon, and Gross Alpha are naturally occurring deposits in the bedrock (Brutsaert *et al.* 1981; Ayotte *et al.* 2003; Banning *et al.* 2013).

Data from private wells in the region provided by Raritan Headwaters' (RHA) Well Test Program indicate that about 16% of wells exceed the NJ drinking water standard (MCL) for arsenic (In 2006, the NJ Department of Environmental Protection set an MCL for arsenic at 5 ppb to achieve a risk level of one in one million excess cancer risk over a lifetime of exposure. The current federal standard of 10 ppb set by the U.S. EPA does not meet the level of protection prescribed by the New Jersey Safe Drinking Water Act. EPA considers cost in setting federal standards, which is not permitted under New Jersey law.); 3.5% exceed the MCL for Gross Alpha; 9.3% exceed the federally proposed standard for radon; 15% fail for total coliform bacteria; and while less than 2% of wells fail for nitrate (NO₃), they often exhibit levels above the 1–2 ppm natural background levels and are at levels that may be harmful to pregnant women and infants (MacDonald & Thomas 2016). The percentage of failures varies geographically with some municipalities having over 42% of wells fail for arsenic, whereas others have only 1% (NJDEP 2016). Furthermore, the levels of contaminants and the quality of drinking water from wells can change, which requires continual monitoring (MacDonald & Thomas 2016).

RHA has over 30 years of data from over 14,000 samples provided from private well owners in the watershed as part of our Well Test Program. Each municipality in the Upper Raritan region partners with RHA annually to provide reduced cost water testing through the RHA Community Well Testing Program (Figure 1). Despite partnering with local municipal governments to implement the annual community well tests and varying levels of public relations leading up to each well test event, RHA has found that only 2–9% of residents on private wells participate each year. In a survey conducted by RHA (Tippet & MacDonald 2017), 66% of residents indicated that they had never tested their well water for arsenic. Seventy percent of respondents indicated the presence of more vulnerable members in the household including children under 12, senior citizens, and those with chronic illnesses or symptoms. This survey confirmed that there is still a general lack of awareness

Table 1 | Health effects from exposure, sources, drinking water standards and recommendations for five common well water contaminants included in this study (NJDEP 2009; USEPA 2016)

Test	Reasons to test	Possible sources of contamination	EPA or NJDEP MCL	Frequency of testing
Arsenic (As)	Causes increased risk of cancers, gastrointestinal ailments, diabetes and cardiovascular impacts	Naturally occurring in bedrock deposits, wood preservatives and historical application of arsenic-containing pesticides	5 ppb (NJDEP)	Every 3–5 years; annually if arsenic detected at or near the MCL
Gross Alpha	Can be ingested or inhaled as gases that are released from the water into the air. Exposure to Gross Alpha emitters in drinking water can lead to lung cancer	Natural deposits of radioactive minerals (containing radium and/or uranium) may emit alpha radiation which can enter the home through well water	15 pCi/L; further testing recommended if Gross Alpha exceeds 5 pCi/L	At least once
Total coliform bacteria and <i>E. coli</i>	Indicative of potential fecal contamination and the potential presence of other harmful pathogens	Cracks in well casing, faulty seal or seepage near the well, septic system problems, improperly functioning septic systems, stormwater runoff, animal waste, and seepage from fertilized land	No acceptable limit; should be absent from drinking water	Annually
Radon	Can be ingested or inhaled as gases are released from the water into the air. Exposure to radon in drinking water can lead to lung and other cancers	Naturally occurring, produced by the breakdown of uranium in soil, rock, and water. Can enter the home through well water	There is no state or federal standard; we use the EPA-proposed standard of 4,000 pCi/L	At least once
Nitrate (NO ₃) (measured as nitrogen)	High levels of nitrates are harmful to infants and pregnant women; alters ecological communities by favoring overgrowth of some organisms normally limited by nitrogen (e.g., algal blooms)	Cracks in well casing, faulty seal or seepage near the well, septic system problems, stormwater runoff, and seepage from fertilized land	10 ppm	Annually

and/or concern for this potentially health-threatening pollutant in our water supply. In addition, most residential private well owners test for only total coliform bacteria, *E. coli*, and nitrate, which are also harmful, but not the other potential contaminants that pose serious threats. The survey also indicated that municipal involvement in publicizing the event and providing access to well test kits through their municipal offices greatly boosts the percentage of residents participating (Tippet & MacDonald 2017). Locally generated awareness campaigns targeting arsenic-affected communities in Quebec, Canada have been found to be four times as effective as mass media campaigns at motivating water testing for arsenic. However, the testing rates in this area still remained a low 16% compared with the earlier 4% before intervention through targeted public outreach (Renaud *et al.* 2011). Residents in arsenic-affected communities tend to underestimate

the negative health impacts of arsenic despite the risks, either because they do not perceive a risk to themselves or because a combination of norm, ability, and attitude barriers influence their behavior (Flanagan *et al.* 2015). Despite low testing rates, analysis of survey data found that well owners in Quebec who said an acquaintance had already tested for arsenic were up to 11 times more likely to decide to test for arsenic themselves, demonstrating the power of social norms (Renaud *et al.* 2011). The explanations for why well owners are not testing are varied. Cost and convenience are known obstacles to regular well testing (Pyrch 1999; Hexemer *et al.* 2008). Some are unaware of the health risks or choose to not test for other reasons (e.g., they drink bottled water). Water contaminants are generally odorless, colorless, and tasteless. Acute symptoms of contamination rarely occur, and the specific causes of chronic illness are more difficult to

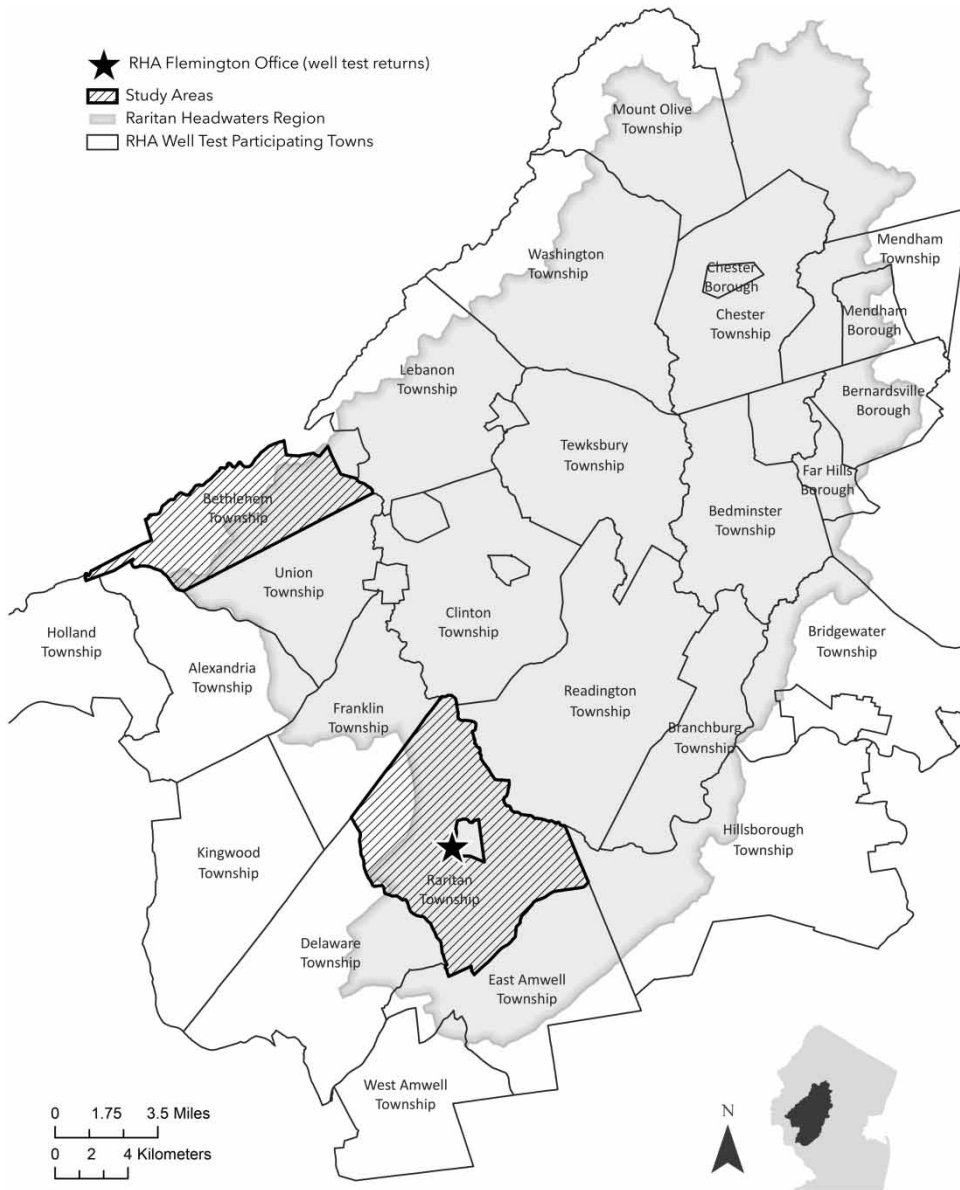


Figure 1 | Map of the Upper Raritan/North and South Branch Raritan Watershed Region (WMA8) showing Bethlehem and Raritan townships (study areas), the location of the RHA office in Flemington (well test return), and the towns that participate in the Community Well Test Program.

determine. Often, an assumption is made that the water is safe and testing is unnecessary. People also tend to be optimistically biased, believing their risk to be lower than others (Weinstein 1989).

Finding ways to better communicate to private well owners the health risks associated with well water and the need to test and treat for a variety of common contaminants is needed if we are to reduce exposures and illness.

Targeting residents whose wells are most at risk for having levels of regulated contaminants above the drinking water standard is a potential way to efficiently reach individuals. Providing residents with warnings that wells close to their own property have failed to meet safe drinking water standards will potentially increase the perception of personal health risk and thereby lead to the desired health actions of testing and subsequent treatment.

This study explored whether knowledge of nearby wells exceeding the drinking water standard for five common contaminants influences the likelihood to conduct water quality tests among residents. Additional questions included whether the likelihood to test varies depending on the contaminant of focus, whether follow-up treatment is initiated where well water exceeds drinking water standards, and whether well test data can be used to predict neighboring wells at high risk for contamination. The findings will have broad applicability to local, regional, state, and federal policies pertaining to public outreach and regulations regarding testing and treatment requirements.

METHODS

Geographic scope

The study focused on two of the region's townships, Bethlehem and Raritan, located in Hunterdon County in the Upper Raritan Region of NJ, USA (Figure 1). The Upper Raritan or North and South Branch Raritan Watershed Region (WMA8) is the largest watershed within the Raritan River Basin and the New Jersey Highlands Region, and is the source of clean drinking water for more than half the state's population. The 1,217 km² (471 mi²) watershed provides well water to the residents of 38 municipalities in Hunterdon, Morris, and Somerset counties and drinking water to more than 1.5 million residents that live beyond the watershed in the densely populated towns and cities in northeastern New Jersey. The region includes the fractured bedrock aquifers of the Newark Basin including mainly the Brunswick aquifer, Lockatong and Stockton formations (Herman *et al.* 1998), along with some limestone aquifers and buried valley aquifers where glaciers deposited sand, gravel, and clay materials. These resources are threatened by continued degradation caused by numerous stressors associated with human activities. There have been large-scale changes in land use in the watershed first with a large-scale conversion of forest to agricultural land over the last century and in the past several decades with a large-scale conversion of farmland and forestland to urban/suburban development (MacDonald & Thomas 2016; RSRRI 2016). These changes have likely influenced

groundwater quality and thus drinking water from private wells.

Data collection and analysis

For nearly six decades, RHA, a nonprofit 501 c(3) environmental organization, has worked to protect clean water in the North Branch and South Branch Watershed Region of the Raritan River (Upper Raritan; WMA8). RHA has been testing water quality in private wells since 1974 as part of its Well Test Program (www.testmywell.org). This is the oldest community well test program in the country and currently tests up to 1,500 wells per year in the region. The wealth of groundwater data obtained from the program provides the opportunity to explore trends in water quality over time, geographic patterns, and also provide the public with information on their private well drinking water supply. Private wells in Bethlehem and Raritan townships were selected from the program database if they exceeded the MCL for arsenic, Gross Alpha, *E. coli*, and/or nitrates or if radon was detected over the federal guideline of 4,000 pCi/L (there is no MCL for radon) for the period 2012–2018. Five hundred and thirty-two wells that exceeded one or more of the five contaminants of interest were identified. The number of wells in the database above the MCLs for each of the contaminants is outlined in Table 2.

Well locations in Raritan and Bethlehem Townships identified as having one or more contaminants exceeding the drinking water MCL were geocoded and mapped in ArcGIS (ESRI, Inc.). All parcels within a 304.8 m. buffer of each of the well points were selected. A spatial join

Table 2 | Wells tested by RHA in Bethlehem and Raritan that exceeded the MCL for at least one of the five contaminants of interest from 2012 to 2018

Contaminant	# of wells exceeding	MCL
Arsenic	344	5 ppb
Nitrates	53	10 ppm
<i>E. coli</i>	47	Should be absent
Gross Alpha	12	15 pCi/L
Radon	76	4,000 pCi/L ^a
Total	532	

The addresses of these wells were used to generate a list of neighboring wells within 304.8 m of the property boundary.

^aFederal guideline.

(ArcMap function that joins tables based on the location) of the parcels to the buffers was performed, creating a list of 2,909 parcels with potential wells within a 304.8 m buffer. Parcel owners were joined to the Parcel IDs, government-owned, and commercial properties were filtered out and a mailing list was created.

Institutional Review Board (IRB) approval for research utilizing human subjects was received from the Rutgers IRB Authority prior to mailing. In total, 2,597 letters were mailed. This included 2,106 specific, local letters mailed to residents in Raritan and Bethlehem townships alerting them to the occurrence of elevated contaminant levels of arsenic, nitrate, Gross Alpha, radon, and/or *E. coli* in wells located within a 304.8 m radius of their property (Table 3). All letters included additional information about the specific contaminant(s) of concern-only but mentioned that testing options for other contaminants existed. In addition, 491 general, regional (control) letters were sent to randomly selected residences in Raritan Township and Bethlehem Township informing the residents that wells in the region are at risk of contamination from *E. coli*, arsenic, nitrates, uranium, lead, and/or radon (Table 3). Control letters included a general fact sheet on private well testing. All letters included an offer to test their well for a reduced rate through RHA's Well Test Program which utilizes a NJDEP-certified water testing laboratory (Garden State Labs, Hillside, NJ). Letters included a statement that this study was part of a health initiative by Raritan Headwaters

and Rutgers University to develop effective outreach on testing and treating for contaminants to private well owners. An online survey was created, and a link to the survey provided in all letters where residents could respond if they chose not to take advantage of the testing program.

The residents' responses and specific test requests were recorded in a master spreadsheet of all letter recipients to monitor response rate and testing. Kits were assembled and placed in an easy to access pick up area, open 24 h/day, at RHA's Main St., Flemington location (Figure 1). The kits included prepared sample bottles, detailed instructions, an information form, and a chain of custody form for the state-certified water testing laboratory. Contact information for RHA's Well Test Program Manager was included, so there was a point of contact for residents to use if they had questions. Participants were instructed to return well test samples to the Raritan Headwaters Flemington office on one of six designated mornings, but accommodations were made for those who requested a different drop off day. Samples were then picked up the same morning by the state-certified laboratory for processing. Participants were notified of positive bacterial sample results within 2 days, and all other results were reported to the participant within 3 weeks of sample return via email (if one was provided) or by USPS (if an email was not provided). Results of the water quality tests were recorded and communicated to the resident once received back from the laboratory. In September 2019, a follow-up telephone survey was conducted of all participants who had exceeded the MCL to determine if they were drinking their well water, if they had treated their water and why or why not, and if they were more or less confident that their water was safe as a result of testing.

In order to determine if the rate of exceedances was higher in wells within 304.8 m than randomly selected wells in the towns, results data from all well tests in Raritan and Bethlehem townships between 2012 and 2018 were pooled for each contaminant, respectively.

Chi-square tests of independence were performed to determine if the likelihood of testing (yes, no) and treating (yes, no) was dependent on several categorical variables including the type of letter (specific, general), municipality (Bethlehem, Raritan), number of specific contaminants (multiple, single), and type of contaminant (arsenic, *E. coli*,

Table 3 | Numbers of letters sent by category (specific/local with subcategories of single- or multi-contaminant and general/regional), #/percent responses and #/percent tested

Letter type	# Letters	Total responses	% Response	# Tested	% Tested
Specific/local letters	2,106	236	11.2	172	8.2
Single contaminant	1,915	213	11.1	155	8.1
Multiple contaminants ^a	191	23	12.0	17	8.9
General/regional letters	491	22	4.7	11	2.2

^aSpecific/local letters included 38 arsenic and *E. coli*; 63 arsenic and nitrate, 5 arsenic, *E. coli* and nitrate; 11 radon and arsenic; 20 Gross Alpha and arsenic; 7 radon and Gross Alpha; 45 radon and nitrate.

Gross Alpha, nitrate, and radon). In addition, the likelihood of exceeding the MCL for neighbors of wells that exceeded was compared with the likelihood of exceeding in all wells sampled through RHA from 2012 to 2018 by township and combined for each respective contaminant. The null hypothesis that the categorical variables were not related was rejected at p -values less than 0.05 for all tests.

RESULTS

As of 1 August 2019, 258 (9.9%) of recipients of the letters responded to the letter by either calling in with questions and/or requesting a well test kit to test for the suggested, or additional, contaminants. Tables 3 and 4 provide a summary of the numbers of letters sent, the percent responding to the letter, and the percent testing. Eighteen of the kits that were requested were never picked up, and 30 kits that were picked up were never submitted for testing. There were only four responses to the online 'opt out' survey, all of which indicated that the reason they chose not to test their well at the time was that they had recently done so and/or they test on a regular basis. A total of 183 wells (7.0%) were tested as a result of the mailing.

Likelihood of residents' testing their private well increases with notification about potentially harmful contaminants in a well within 304.8 m of a resident's property over the receipt of general letter regarding common well contaminants.

- a. Letter type (specific/local or general/regional) \times response type (test or not test)

A chi-square test of independence was performed to examine the relation between letter type (specific contaminant/local results or general contaminants/

regional results) and decision to test. The relation between these variables was significant, $\chi^2 (1, N = 2,597) = 21.353, p < 0.001$. Individuals who received specific letters were more likely to test their well than were individuals who received a general letter. The two townships when analyzed separately demonstrated a similar pattern in that individuals who received the specific letters were more likely to test their well than individuals who received a general letter. For Bethlehem, the chi-square test of independence showed the relation between these variables was significant, $\chi^2 (1, N = 375) = 5.004, p = 0.025$. For Raritan, a chi-square test of independence also showed that the relation between these variables was significant, $\chi^2 (1, N = 2,222) = 16.797, p < 0.001$.

Rate of response variations among the contaminants based on the perception of risk or the communicated risk to health.

- Contaminant type (arsenic, bacteria, nitrate, Gross Alpha, and radon) \times response type (test or not test).

An analysis of the responses to letters for individual, specific contaminants-only (multi-contaminants removed) revealed that the type of contaminant did not influence the likelihood of testing, $\chi^2 (4, N = 1,911) = 6.802 (p = 0.147)$.

- Contaminant # (single or multiple) \times response type (test or not test)

A chi-square test of independence was performed to examine the relation between the number of contaminants in specific letters (single and multiple) and decision to test. The relation between these variables was not significant, $\chi^2 (1, N = 2,106) = 0.101, p = 0.750$. Individuals who received specific letters reporting more than one contaminant were not more likely to test their

Table 4 | Numbers of letters sent for specific-local (single- and multi-contaminant) by contaminant type, percent returned, and percent tested

Contaminant type	# Letters	Total responses	% Response	# Tested	% Tested	Mean concentration	Range (minimum–maximum)	SD (+/–)
Arsenic	1,606	194	12.0	140	8.7	0.004 ppb	0–0.068	0.006
Nitrate	288	27	9.4	20	6.9	4.022 ppm	0–13.3	2.62
Gross Alpha	102	13	12.7	9	8.8	5.012 pCi/L	0–22.5	6.313
Radon	249	20	8.0	14	5.6	2,073 pCi/L	209–10,023	2,091
<i>E. coli</i>	57	6	10.5	4	7.0	0.042 (present/absent)	0–1	0.201

The concentrations of contaminants are for all tests resulting from all participants who tested as part of this study and include mean, range, and standard deviation (SD).

well than were individuals who received a specific letter for one contaminant.

Treatment of identified contaminants among participants

Forty-five wells were at or exceeded the MCLs for the contaminants tested (see Table 3 for a breakdown among contaminants). Of these, 22 residents participated in a subsequent survey intended to gather information about follow-up treatment. Thirty-six percent of the participants treated their well water as a result of their test exceeding the drinking water standard. The most common reasons for not treating were the belief that the contaminant was not a concern or that the existing treatment was sufficient, or that drinking bottled water replaced the need to treat the well water. Prior to testing, 36% drank bottled water, 23% drank unfiltered well water, and the rest drank filtered well water. Ninety-five percent of participants did not switch their water source after learning that their well exceeded the drinking water standard for one or more contaminants. After testing, 55% reported that they were very confident and 36% reported that they were somewhat confident in their well water being safe to drink, and a small percentage (9%) reported that they were not confident. Testing and finding the water did not meet drinking water standards increased the confidence in 64% of respondents and decreased the confidence in 14%. Most respondents (77%) felt that the information provided about treatment options

along with their test results was helpful to them, and 91% of respondents plan to test their well water again in the future.

Predicting probability of contaminant concentrations exceeding drinking water standards to inform targeted, cost-effective public outreach

The likelihood of local wells being contaminated if a neighbor within 304.8 m exceeded the MCL was explored for all five contaminants (Table 5). The likelihood of exceeding for at least one of the contaminants was 18% for those receiving the letter about a specific exceedance locally, whereas the likelihood was 5% of those testing their wells in the two municipalities pooled between 2012 and 2018. The likelihood of exceeding the MCL was compared between wells tested as a result of receiving a specific-local letter and the RHA community well test database for the five contaminants, respectively, for each township as well as for townships combined. For Raritan Township, none of the contaminants exhibited a greater likelihood of exceeding the MCL if a neighbor had failed when compared with the percentage in the RHA database for 2012–2018. None of the towns showed a higher likelihood for exceeding the MCL for arsenic or Gross Alpha if a neighbor exceeded for those contaminants, respectively. However, for Bethlehem Township and both towns combined, *E. coli* and nitrate had a higher likelihood of exceeding the MCL if a neighbor's well exceeded [for Bethlehem, *E. coli* χ^2 (1, $N = 112$) = 17.493,

Table 5 | For individual wells tested, percentage exceeding for contaminants for those receiving specific-local letter informing them that a neighbor had exceeded the MCL (% left) and percentage exceeding for all RHA Well Test data for the period 2012–2018 (% right)

Contaminant	Bethlehem township		Raritan township		Combined towns	
	% Exceeding		% Exceeding		% Exceeding	
	Neighbor	RHA data	Neighbor	RHA data	Neighbor	RHA data
Arsenic	No data	0	18.4	24	18.4	21.4
<i>E. coli</i>	50.0	1.8	0	0.6	25.0	0.8
Gross Alpha	0	0	16.7	6.9	11.1	5.1
Nitrate	40.0	5.4	0	0.4	10.0	1.4
Radon	33.3	21.4	0	4.2	26.7	9.0

In addition, bold entries indicate cases where the likelihood of exceeding is greater for wells that are within 304.8 m of a well that exceeded for a particular contaminant when compared with the general population of wells tested by RHA from 2012 to 2018 (based on χ^2 , $p < 0.05$, see Appendix for statistics).

$p < 0.001$, and nitrate $\chi^2 (1, N = 115) = 8.818, p = 0.003$ and for combined townships, *E. coli* $\chi^2 (1, N = 599) = 23.387, p < 0.001$, and nitrate $\chi^2 (1, N = 604) = 8.846, p = 0.003$. Furthermore, for both towns combined, but not individual townships, radon had a higher likelihood of exceeding the federal guideline if a neighbor's well exceeded when compared with the combined township data from 2012 to 2017, $\chi^2 (1, N = 114) = 3.983, p = 0.046$.

Eight of the 20 wells tested for nitrates had elevated levels of nitrates at or over 8 mg/L (ppm), but only two were over the MCL of 10 mg/L. While there were no radon fails in Raritan, one of the radon letter recipients also tested for Gross Alpha and failed.

DISCUSSION/CONCLUSIONS

The central tenet of this study that individuals receiving specific letters about contaminants in local wells are more likely to test their well than were individuals receiving a general letter about regional contaminants was supported by the data. However, even though the targeted letters had a higher response rate (11.2%) than the general letters (4.7%), those numbers indicate in both cases that a large majority of residents are not responding with the health action of testing and treating when provided with information on potential contaminants in their private well water. This means that there is more work to be done on effectively reaching the goal of private well owners taking the initiative to ensure the safety of their drinking water.

Possible explanations for the low numbers are many. The lack of understanding of the risks was indicated in that the type of contaminant did not influence the likelihood of testing. This suggests that residents perceived a similar risk (or lack thereof) among contaminants. It was also surprising that individuals who received specific letters reporting more than one contaminant were not more likely to test their well water than were individuals who received a specific letter for one contaminant. The number of contaminants did not seem to influence perceived risk, which further indicates a possible lack of understanding.

From the telephone survey, it was learned that 36% of respondents treated their well water as a result of their test showing an exceedance in one or more contaminants,

while the remaining 64% did not. We learned that there is a certain level of optimistic bias that likely affects testing and treatment as evidenced by many, saying the reason for not treating was the belief that the contaminant was not a significant health risk or that the existing treatment was fine. Also, the survey brought to light that many people (36%) in the study were relying on bottled water prior to testing and continued to do so after testing, and thus, they did not see a need to treat the water. The number relying on bottled water is likely higher, given that most residents did not respond to the letters. The tendency for residents to drink bottled water warrants further study as it indicates an assumption that local groundwater sources of drinking water are not trusted as being safe despite the lack of scientific data to support this assumption. It is possible that people are afraid of learning about contaminants in their drinking water because they do not know they can treat the water and remove these contaminants. Positive messages that empower individuals with knowledge that they can do something to protect the health of their family by testing and treating their water should help to address this obstacle.

Another explanation for not testing is that cost and convenience are obstacles for some. Several residents indicated that the cost of testing was prohibitive. The proximity of residents to RHA's Well Testing office (where kits were picked up and subsequently dropped off) and the associated level of convenience may have been a factor in the level of response to the letter and subsequent testing. The potential effect of proximity was supported by a greater percentage of residents in Raritan Township (1–6 mile distance from the RHA office) that tested their wells than residents in Bethlehem Township (15–22 miles distance from the RHA office), although there was no significant statistical difference. Also, a number of residents responding to the letter by email or phone failed to pick up the well testing kits they ordered, which supports that convenience may have been a factor.

Still, 64% of residents who tested as part of this study were drinking filtered or unfiltered well water prior to testing, which means many do rely heavily on their private well water. Thus, a large population of people are in need of compelling scientific information on the risks associated with contaminants in their private well water and incentives for testing and treating their water. That testing was a

positive experience was evidenced by reporting of increased confidence and the usefulness of the information provided in the letter as well as follow-up information on treatment. Testing tended to promote a tendency for residents to report they plan to test again in the future. However, targeting effective outreach to get the large majority to test remains a challenge. Future studies might explore further how different sources of information will influence health actions. The letter mailed to residents originated from RHA (a regional nonprofit environmental group) and Rutgers University (a respected academic institution in the region). Future studies should explore other partnerships in providing information including municipal governments, schools, health departments, and healthcare providers, and compare whether health actions are influenced by the source of information. In addition, direct mailings may not be the best route for reaching people. Of respondents who spoke with RHA's Well Test Program staff about the letters they received, many at first were skeptical about the letter; some believing it was intended to scare them into testing and that we were trying to sell them a product. However, after the conversation with RHA and Rutgers staff, most expressed a better understanding of the health risks of contaminants in their well water and the need to test and treat. Many indicated relief and gratitude for being informed of the risks. Furthermore, respondents who had received a letter indicating a local exceedance of one or more contaminants were more likely to test for additional contaminants if they spoke with a staff member than if they responded via email or left a voicemail to order a testing kit. In the latter case, they tested only for the specific contaminant, even though USEPA guidelines recommend testing private wells for some contaminants (i.e., total coliforms/*E. coli* and nitrate) every year.

Outreach campaigns are expensive, and the possibility of finding ways to be more efficient in targeting residents at greatest risk of exposure was explored. The results indicated that there is some potential to use wells that exceed an MCL to identify other wells at risk of exceeding in the geographic vicinity for *E. coli*, nitrates, and radon but not for arsenic and Gross Alpha. Perhaps, there are variables other than contaminants in neighbors' wells that need to be explored including past and current land use, geology, depth of well, well age and type, age of dwelling and

septic systems, and well and septic service history for developing predictive models for use in identifying higher risk of exposure to contaminants.

Given that only a small percentage of private wells in the watershed are tested on a regular basis, there remains a critical need for education and outreach about where well water is coming from and what levels of contaminants it may contain. In addition, education and incentives to improve our practices on the land and address anthropogenic sources of well water contamination will go a long way toward protecting all of our water resources – both groundwater and surface water. We also need to better inform residents that for the most part, our groundwater is clean and can be relied upon as a source of safe drinking water as long as precautions are taken to test and treat on a regular basis; bottled water is not a good long-term alternative in most cases due to reasons such as the high cost to the consumer and generation of plastic waste. This study indicates that better approaches are needed in order to encourage residents to respond with the desired health actions of testing and treatment of their private well water. While letters about specific, local contaminants do help target residents and boost testing to some extent, more research is needed on how to get the majority of residents to respond. Further studies into how the originating source of outreach information impacts perceived reliability of data are needed. In addition, developing predictive models of likelihood of exceedances for contaminants will help to make outreach more efficient and successful in engaging those most at risk.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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