Detecting community response to water quality violations using bottled water sales

Maura Allaire[a,1], Taylor Mackay[b], Shuyan Zheng[c], and Upmanu Lall[c,d]

[a]Department of Urban Planning and Public Policy, University of California, Irvine, CA 92697; [b]Department of Economics, University of California, Irvine, CA 92697; [c]Columbia Water Center, Columbia University, New York, NY 10027; and [d]Department of Earth and Environmental Engineering, Columbia University, New York, NY 10027

Edited by Arun Agrawal, University of Michigan, Ann Arbor, MI, and approved August 28, 2019 (received for review March 28, 2019)

Drinking-water contaminants pose a risk to public health. When confronted with elevated levels of contaminants, individuals can take actions to reduce exposure. Yet, few studies address averting behavior due to impaired water, particularly in high-income countries. This is a problem of national interest, given that 9 million to 45 million people have been affected by water quality violations in each of the past 34 years. No national analysis has focused on the extent to which communities reduce exposure to contaminated drinking water. Here, we present an assessment that sheds light on how communities across the United States respond to violations of the Safe Drinking Water Act, using consumer purchases of bottled water. This study provides insight into how averting behavior differs across violation types and community demographics. We estimate the change in sales due to water quality violations, using a panel dataset of weekly sales and violation records in 2,151 counties from 2006 to 2015. Critical findings show that violations which pose an immediate health risk are associated with a 14% increase in bottled water sales. Generally, greater averting action is taken against contaminants that might pose a greater perceived health risk and that require more immediate public notification. Rural, low-income communities do not take significant averting action for elevated levels of nitrate, yet experience a higher prevalence of nitrate violations. Findings can inform improvements in public notification and targeting of technical assistance from state regulators and public health agencies in order to reduce community exposure to contaminants.

drinking water | violation | water quality | health | risk reduction

Securing safe water for communities across the United States is a growing concern. When confronted with impaired drinking water, individuals can take actions to reduce exposure, such as purchasing bottled water. However, little is understood about how communities respond to drinking-water contaminants, especially in high-income countries (1). This study uses consumer purchase behavior to shed light on how communities across the United States respond to violations of the Safe Drinking Water Act (SDWA). This addresses a problem of national interest, given that 9 million to 45 million people have been affected by drinking-water quality violations in each of the past 34 y (2).

Critical findings from this study include an understanding of how communities respond to water quality violations. Do communities undertake averting actions by purchasing bottled water? If so, which types of communities? And how do actions differ across violation type?

Understanding how communities respond to SDWA violations could aid public health agencies, water systems, and environmental quality regulators to direct assistance to communities most in need. At present, there is no systematic approach for identifying communities for prioritized assistance. Furthermore, it is unknown whether public notices spur adequate action to reduce exposure to impaired water. Federal regulations for notices, under the Public Notification Rule, have not been updated in 2 decades and do not utilize modern forms of communication. Identifying the types of communities and violations for which greater averting action is needed could inform improvements in public announcements and ensure populations across the United States are knowledgeable about their water quality.

Besides understanding averting behavior, the magnitude of bottled water sales per capita has implications for benefits attributable to safe drinking-water regulations for public water supplies. Bottled water use is increasingly common in the United States, with sales of over $18 billion in 2017 (3). As public water customers shift toward bottled water, benefits of SDWA regulations diminish.

Few studies have assessed the extent to which households take averting actions in response to water quality violations (e.g., refs. 4–8). Previous studies that tracked bottled water use as an averting action are mostly limited to cross-sectional, self-reported data from a single location or event (e.g., refs. 6 and 7). One panel study assesses the association between sales of bottled water and maximum contaminant level (MCL) violations in California and Nevada (8).

More commonly, studies address compliance with boil water notices, which tend to be issued as a precaution for possible biological contamination (9). A metaanalysis found that, among customers who are aware of notices, compliance with averting exposure ranged from 36 to 98%, with a median of 68% (9). When responding to boil water notices, bottled water purchase is generally preferred to boiling (5, 10, 11). Thus, our focus on bottled water can provide considerable insight into the extent to

Significance

This study addresses a problem of national interest given that elevated levels of drinking-water contaminants affect communities across the United States. While violations of quality standards are tracked by the US EPA, it is unknown how communities respond and whether appropriate measures are taken to avoid exposure. Regulations that guide public notification of violations have not been updated in 2 decades, and there is no systematic approach for prioritizing assistance. Understanding the extent of community averting actions could improve public notification protocols and targeting of technical assistance from state regulators and public health agencies. We assess how averting behavior differs across violation types and community demographics. Such knowledge can improve public communication in order to reduce adverse health consequences.

Author contributions: M.A. and U.L. designed research; M.A. performed research; M.A., T.M., and S.Z. analyzed data; and M.A. wrote the paper.

The authors declare no conflict of interest.

This article is a PNAS Direct Submission.

Data deposition: Regression data associated with this research are available at Dataverse (https://dataverse.harvard.edu/dataverse/allaire).

[1]To whom correspondence may be addressed. Email: maura.allaire@uci.edu.

This article contains supporting information online at www.pnas.org/lookup/suppl/doi:10.1073/pnas.1905385116/-/DCSupplemental.

First published September 30, 2019.

which averting actions are taken. This study does not assume that bottled water is necessarily of higher quality than public tap water, since bottlers provide limited publicly available data. Nonetheless, bottled water purchase is a recommended action in public notices. Furthermore, bottled water use is increasingly common in the United States, representing nearly 24% of total beverage sales. The average American now consumes more than twice as much bottled water compared to 20 y ago (3), partly due to perceived health and safety concerns (12).

Besides specific water contamination events, some studies address response to ongoing concerns (e.g., refs. 13 and 14). Jakus et al. (13) assess averting actions, including self-reported bottled water expenditures, for 201 households in locations with arsenic contamination. Wrenn et al. (14) analyze the perceived risk of shale gas development and bottled water sales, using repeated cross-sections of household-level purchases. Little is known about how individuals respond differently to short-term water quality concerns compared to recurring problems (5). Reduced confidence in tap water has been found after drinking-water quality lapses (15, 16). Our study assesses whether the response of bottled water sales to violations declines over time, due to habitual drinking of bottled water. Additional description of past studies can be found in *SI Appendix*, *SI Literature Review*.

To overcome the limitations of past assessments, we conduct a national, panel study that explores how averting actions differ across locations, violation type, and community demographics. This research builds on prior studies that are limited in geographic scope. We construct a panel dataset of county-week observations that includes 18,814 community water systems (CWSs) in 2,151 counties from 2006 to 2015. We combine information on health-related violations, sales of bottled water, and community demographics. Averting actions are assessed using fixed effects regression models. Key study objectives are to 1) determine the extent of averting action, as measured by response in weekly bottled water sales to quality violations, and 2) identify the types of communities and violations with lower response, which can be used to target assistance and improve public notification.

Background

When a violation occurs, CWSs must notify the general public. The Public Notification Rule provides guidance to enable water systems to deliver informative messages and protect public health. These provisions were part of the original SDWA in 1974 and were modified in 1986 and 2000. The most recent revisions in 2000 clarified how violations can be classified into tiers, with specific protocols and timing for issuing notices. Prior to this, the majority of water systems failed to comply with public notification provisions (17).

The US Environmental Protection Agency (EPA) categorizes violations based on the immediacy of public health risk and requires notification to customers when CWSs are noncompliant. Tier 1 violations are considered to be the most serious type of violation and pose an immediate health risk. Meanwhile, Tier 2 violations have the potential for severe health effects, generally after prolonged exposure.

When a violation occurs, CWSs must notify customers as soon as practical, but within 24 h for a Tier 1 contaminant and within 30 d for a Tier 2 violation (Table 1). These deadlines begin once a system is notified by the primacy agency of noncompliance, which also marks the beginning of the violation period. The violation period ends once mitigation action is taken and the system returns to compliance.

Public notifications of Tier 1 violations must be issued via one or more delivery modes—radio, television, hand delivery, posting in conspicuous locations, or another method approved by the state-level agency responsible for enforcing the SDWA (18, 19). Notices for Tier 2 violations have the option of being mailed and can be included, for example, as an insert in water bills. In some states, other approved delivery modes include newspaper, recorded telephone messages, and email. Notices must be provided to all customers who receive water, not only those who are billed. Given that the most recent revisions of the Public Notification Rule were nearly 2 decades ago, some of the delivery modes might now be antiquated and fail to reach substantial portions of some communities.

Information content and mode of delivery can vary across states, since each primacy agency can specify slightly different protocols as long as national standards are met. The affected water system is required to consult with the primacy agency and typically also works with the county health department. State-level differences also exist in terms of requirements to notify customers when violations are resolved. Thus, controlling for county-level effects is an important feature of our analysis.

Bottled water is one recommended averting action commonly included in public notices. Standards for bottled water are regulated by the Food and Drug Administration (FDA) for bottled water sold in interstate commerce. FDA quality standards generally match MCLs established by the EPA for public water supply. Yet, the quality of bottled water is not widely understood, since a public database is not currently available as it is for public water supply. Furthermore, bottled water that is produced and sold in a single state is not regulated by the FDA, although state public health agencies can develop standards (20). Sampling

Table 1. Public notification requirements for Tier 1 and Tier 2 violations

Violation tier	Deadline for first notice	Repeat notices	Delivery modes	Contaminants
1	24 h	As directed by primacy agency	Broadcast media (radio, television) Hand delivery Posting in conspicuous locations Other methods approved by state	Fecal coliform, *E. coli** Turbidity† Nitrate, nitrite‡
2	30 d	Every 3 mo	Mail Hand delivery Other methods approved by state	All other MCL, MRDL, TT violations§

*Fecal coliform and total coliform are regulated under the Total Coliform Rule. Tier 1 violations are triggered by an MCL violation or failure to test for fecal coliform after a repeat sample tests positive for total coliform.

†Turbidity is sampled as an indicator of microbial concerns under the Groundwater Rule and rules related to surface water treatment. A Tier 1 violation can occur due to MCL exceedance or failure to consult with primacy agency within 24 h of MCL exceedance. Elevated levels of turbidity can interfere with disinfection and promote growth of bacteria, viruses, and parasites (e.g., *Cryptosporidium*).

‡Nitrate and nitrite are regulated under the Phase II Rule. A Tier 1 violation can occur due to MCL exceedance or failure to take confirmation sample within 24 h of MCL exceedance.

§Tier 2 violations occur when water systems do not comply with other requirements related to MCL, maximum residual disinfectant level (MRDL), and treatment technique (TT).

protocols differ between bottled water and public tap water. The EPA requires public water testing by certified laboratories, which submit results directly to state regulators. In contrast, the FDA relies on sampling results from bottlers. Therefore, this study does not assume that bottled water is necessarily of higher quality than public tap water, given limited information. Yet, bottled water is considered an alternative water source during violation periods at public water systems.

Materials and Methods

Data. In order to examine the relationship between sales and SDWA violations, we construct a panel dataset of county-week observations of health-related violations and sales of bottled water. Both store-level sales and CWS-level violations were aggregated to the county level. In addition, the study excludes stores that report sales during fewer than 469 wk from 2006 to 2015.

Inclusion criteria restrict the study sample to water systems that have service populations of over 500, began reporting to the US EPA Safe Drinking Water Information System by 2006, and are located within the lower 48 states. The study also only included CWSs, which serve year-round populations of at least 25 people. Very small CWSs serving fewer than 500 people were excluded, since they are more likely to have inconsistent reporting (21) and are subject to different sampling and monitoring requirements. For example, very small systems have less frequent sampling for turbidity, which may lower the likelihood of detecting a violation of the Surface Water Treatment Rules. Since very small systems serve only 1.5% of the US population, excluding these systems is unlikely to considerably alter the generalizability of results.

Methods. A fixed effects model is used to estimate the change in weekly sales of bottled water due to health-related water quality violations. To assemble the underlying data, we match a panel of weekly sales data with violation records for 18,814 CWSs that serve over 280 million people in 2,151 counties from 2006 to 2015. The balanced panel dataset is used to model sales (S) as a function of a violation indicator, weather variables (X), Census variables (Z), and fixed effects for county (α_c) as well as year and week (γ_t). We develop fixed effects models to examine the association between violations and bottled water sales, using the following specification:

$$S_{ct} = \beta_0 + \beta_1\left(\frac{k_{ict}}{7}\right)\left(\frac{p_{ic}}{p_c}\right) + \beta_2 X_{ct} + \beta_3 Z_{cy} + \alpha_c + \gamma_t + \varepsilon_{ct}, \quad [1]$$

where S is the log of bottled water sales in county c in week t. The violation indicator is calculated by taking the portion of the county population that was served by a given water system (p_{ic}/p_c) and multiplying this by the portion of days in the week that the violation was in effect ($k_{ict}/7$). Thus, the violation indicator is equal to a value above zero during all weeks of a violation period. Weather variables (X_{ct}) control for time-varying preferences for bottled water. County fixed effects account for time-invariant factors that affect demand, such as personal preferences. By exploiting within county variation over time, we control for any county-level differences in public notification of violations (Table 1). Thus, we control for average differences across counties in any time-invariant factors. This is an important feature of the analysis, since county health departments are involved with notification content, mode of delivery, and decision to notify customers when violations are resolved. Year and week fixed effects capture temporal and seasonal trends in sales. SEs are clustered at the county level, which relaxes the assumption of normally distributed errors and homoscedasticity.

We examine how averting actions vary across violation types and community demographics. Models are specified for several types of Tier 1 and Tier 2 violations. Violation categories are based on potential health consequences and public notification (*SI Appendix*, Table S1 and *SI Data*). Tier 1 violations are considered to pose an immediate health risk, while Tier 2 violations have the potential for severe health effects after prolonged exposure. The analysis also addresses how averting actions vary based on community demographics, such as below median income and rural areas.

Demand for bottled water may increase if a violation occurs, as consumers substitute away from tap water. Yet, other factors could also influence bottled water purchase, and this jointness in production can complicate efforts to understand health-related reasons for bottled water purchase. Our study addresses this issue of joint production in 3 ways: 1) focusing the analysis on changes in purchases during quality violation events, 2) controlling for year and week fixed effects and weather variables that capture seasonal preferences, and 3) testing whether repeated violations are associated with a lower response of increased bottled water sales, perhaps due to habitual drinking of bottled water. For more detail on our regression analyses, see *SI Appendix, SI Materials and Methods*.

Results

Summary Statistics. National bottled water sales vary seasonally, with peak sales occurring in the summer months (Fig. 1). Sales vary substantially across county-week observations, ranging from \$0.82 million to \$4.2 million (*SI Appendix*, Table S2). In addition, bottled water sales per capita vary considerably across counties (Fig. 1).

Our balanced panel dataset contains 10 y and 2,151 counties, which contain 18,814 CWSs and over 25,400 stores. Over 69% of counties and 95% of the population in the continental United States are represented in this study. Excluded counties are home to 4.6% of the continental US population, and many lack stores that report to the Nielsen database. Many excluded counties are located in the central region of the country. Full summary statistics and variable definitions are provided in *SI Appendix*, Table S2 and *SI Results*.

In our sample, few violations are Tier 1 (less than 7%, or 2,146 violations), while the vast majority are Tier 2 (*SI Appendix*, Fig. S1). Among Tier 1 violations, the majority are pathogens (67%, or 1,438 violations) (*SI Appendix*, Table S3), and seasonal, summertime peaks exist for this violation type (Fig. 2 and *SI Appendix*, Fig. S2). Meanwhile, Tier 1 nitrate violations tend to have a much longer duration (mean duration of more than 101 d) compared to pathogens (mean of less than 30 d) (*SI Appendix*, Table S3). In contrast,

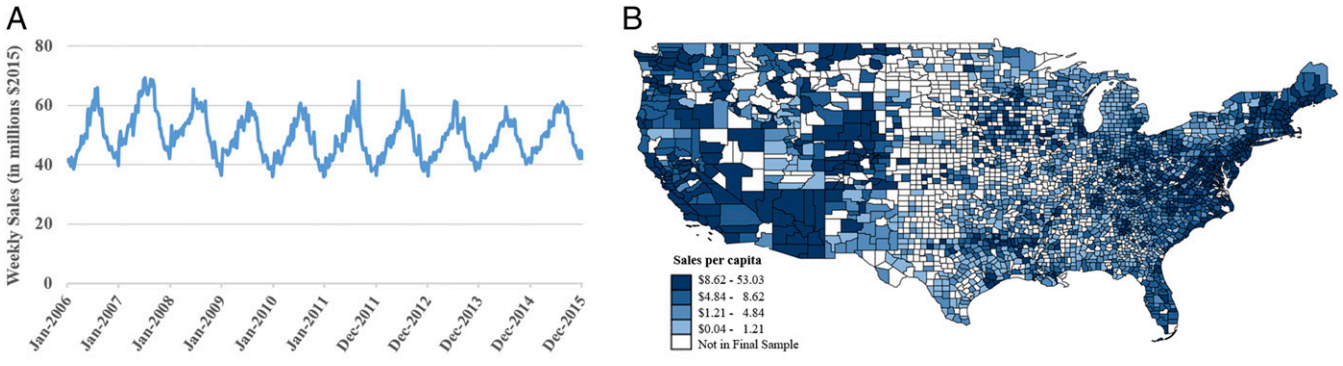

Fig. 1. National bottled water sales. The graph in *A* depicts national bottled water sales for each week during the 2006–2015 study period (in millions \$2015). The map in *B* shows county-level, total bottled water sales per capita during the 2006–2015 study period (in \$2015 per capita). Counties not included in the final sample are mostly attributable to insufficient sales data (*SI Appendix, SI Data*). Over 69% of counties and 95% of the population in the continental United States are represented in this study.

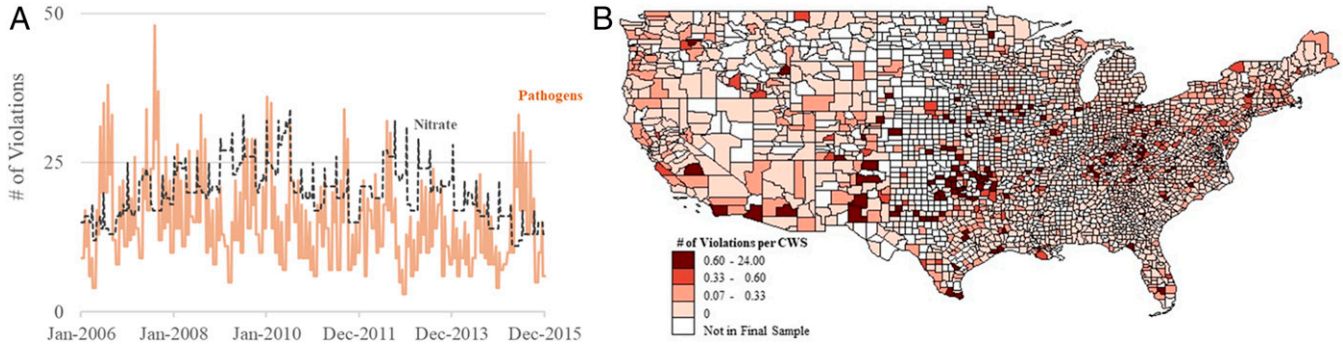

Fig. 2. Tier 1 violations of national primary drinking-water regulations. The graph in *A* shows the number of Tier 1 violations for each week during the 2006–2015 study period. Violation counts are presented separately for those attributable to 2 categorizations—nitrate (dashed gray line) and pathogens (solid orange line). The map in *B* depicts county-level, Tier 1 violations water sales per CWS, during the 2006–2015 study period.

Tier 2 violations last much longer than Tier 1 violations, nearly twice as long, on average. The longer average duration of Tier 2 violations is mostly driven by violations that are not resolved within a few months—some last nearly the entire study period. Geographically, violations are especially prevalent in parts of Appalachia, the Central Plains, and the Southwest (Fig. 2 and *SI Appendix*, Fig. S2). Overall, observations of health-based violations are rare in a given week and county (*SI Appendix*, Table S2).

Across demographic groups, large variation exists in both bottled water sales and violation occurrence (*SI Appendix*, Table S4). Counties with above-median income (referred to as "high income") have higher per capita sales than low-income areas. This holds true for both rural and nonrural areas; therefore, bottled water consumption appears to follow income. Meanwhile, rural areas have a higher prevalence of Tier 1 violations, especially Tier 1 nitrate. Rural areas have more than twice as many nitrate violations per county (0.56) compared to nonrural areas (0.25). This disparity in nitrate violations between rural and nonrural areas increases to 4-fold on a per CWS basis (*SI Appendix*, Table S5). In addition, rural low-income counties have the highest prevalence of Tier 1 violations and nitrate violations, in terms of both average violation counts per CWS across weekly observations (*SI Appendix*, Table S4) and total violation counts from 2006 to 2015 per county and per CWS (*SI Appendix*, Table S5). Therefore, these summary statistics indicate that rural low-income counties are most affected by Tier 1 violations, especially nitrate, and have low bottled water sales.

Regression Results. Our major findings from the regression analysis are that communities take significant averting action in response to violations, yet these responses differ across types of violations and communities.

We find that Tier 1 violations, which pose an immediate health risk, are associated with a 14.1% (±10.0 percentage points) increase in bottled water sales (Table 2). Only a 4.9% (±3.5 percentage points) increase is found for Tier 2 violations, which generally have the potential for health consequences after prolonged exposure. Thus, the public appears to be more responsive to violations with potential for acute health effects and that require public notification within 24 h. Lower response is associated with Tier 2 violations that might be corrected by the time customers receive notification within 30 d.

Our estimates of increased sales due to water quality violations likely represent lower-bound values. The indicator of averting action, purchase of bottled water, does not include other possible actions such as in-home treatment (e.g., boiling, filtering) or purchasing other types of beverages (e.g., soda, juice). Yet, past studies of response to boil water notices have revealed that bottled water is generally preferred to boiling (5, 10, 11). Furthermore, results cannot be generalized to counties excluded from our study, where 4.6% of the continental US population resides. These counties are significantly more rural than our study sample (*SI Appendix*, Table S6).

Averting actions also differ substantially across violation types. While Tier 1 pathogen violations are associated with increased sales of bottled water (14.3% ± 5.7 percentage points), nitrate violations are not (Table 2). The Tier 1 pathogens category includes MCL violations of fecal coliform, *Escherichia coli*, and turbidity (*SI Appendix*, Table S1). Among Tier 2 violations, an increase in sales is associated with pathogen violations (8.8% ± 4.5 percentage points), which include nonfecal coliform, turbidity,

Table 2. Estimated effects of quality violations on bottled water sales

	Tier 1			Tier 2		
Violations	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6
Any	0.141***			0.049***		
	(0.051)			(0.018)		
Pathogens		0.143***			0.088***	
		(0.029)			(0.023)	
Nitrate			0.141			0.040*
			(0.102)			(0.022)
Observations	1,120,666	1,120,666	1,120,666	1,120,666	1,120,666	1,120,666
R^2	0.984	0.984	0.984	0.984	0.984	0.984

Coefficient estimates of β_1 in Eq. **1**, for 6 models. For model 1, the estimate represents the average percent change in sales associated with any type of Tier 1 violation; ***significant at the 1% level; *significant at the 10% level. SEs (in parentheses) clustered at county level. All regressions include year, week, and county fixed effects. In addition, regressions control for all variables presented in Eq. **1**.

Cryptosporidium, and *Giardia lamblia*. In contrast, no significant response at the 95% confidence level is found for "other" violation types (Table 2).

Differences in averting behavior across violation types could be attributable to a variety of factors. These include notification timing and content, risk perception, and population at risk. For example, Tier 1 violations require immediate public notification and are associated with short-term health consequences. In contrast, Tier 2 notifications could take up to 30 d to reach the public, and these notices generally do not instruct customers to avoid direct use of tap water (*SI Appendix*, Table S1 and ref. 18). Limited data exist on notification timing and content associated with specific violations; therefore, it is unclear to what extent purchases are motivated by information received compared to severity of potential health impacts.

Among subcategories of violations, for both Tier 1 and 2, a significant increase in sales is only found for pathogens. This might be attributable to greater familiarity with health impacts and/or risk perception for pathogens such as bacteria and viruses. Nitrate violations are not associated with a significant response, which might be attributable to the fact that nitrate only poses a near-term health risk for infants less than 6 mo old. Public notices for nitrate violations specifically state that infants under 6 mo old should not continue drinking tap water.

Tier 2 other violations are also not significantly associated with increased sales. This might be due to the public having less familiarity with health impacts of these contaminants and perhaps lower risk perception associated with uncertain health consequences in the distant future. In addition, notice content differs considerably between Tier 2 other violations and pathogens. Notices for Tier 2 other violations only state that habitually drinking water with elevated contaminant levels for many years could increase health risks (19). In contrast, notices for pathogens tend to state specific health effects and are required to mention the presence of disease-causing organisms in the water supply.

The analysis also examined how response in sales varies by demographics. This provides insight into which types of communities take averting actions due to impaired drinking water. Rural counties with below median income (referred to as "low income") are found to not have a significant response in bottled water sales to Tier 1 violations, overall (Table 3). Similarly, sales in nonrural high-income counties also are not significantly associated with Tier 1 violations, yet these locations have lower prevalence of violations compared to rural counties (*SI Appendix*, Tables S4 and S5). In contrast, considerable increases in bottled water sales due to Tier 1 violations are found in nonrural counties with low income (13.9% ± 10.4 percentage points) and rural counties with above-median income (28.7% ± 15.4 percentage points).

For subcategories of Tier 1 violations, all 4 demographic categories have significant responses to Tier 1 pathogen violations. The lowest magnitude response is in nonrural high-income counties (11.5% ± 5.5 percentage points), which might be attributable to greater average per capita bottled water sales in these areas. This implies there is less possible response during violation periods, since bottled water use is more prevalent.

Notably, rural low-income counties do not take significant averting action against Tier 1 nitrate violations. This result is not attributable to greater baseline purchases of bottled water in low-income, rural counties, since average sales per capita in these communities are less than in higher-income counties (*SI Appendix*, Table S4). In contrast, rural, high-income counties are responsive to Tier 1 nitrate violations. A large response is an encouraging finding, given the high prevalence of nitrate violations in rural areas. We do not emphasize nitrate results for nonrural counties, since nitrate violations occur considerably less often in these areas.

Differences in changes in bottled water purchases could be due to a variety of factors. Smaller increases in sales could be attributable to 1) individuals not averting exposure, 2) taking other protective actions, or 3) relatively high baseline sales of bottled water during periods without violations. In our study sample, average sales per capita in rural low-income counties are lower than in higher-income counties and similar to low-income, nonrural counties (*SI Appendix*, Table S4). This might indicate that rural low-income counties either are taking alterative protective actions (e.g., boiling or filtering water) or are not averting exposure. If the latter reason is true, this would be a serious concern, due to the high prevalence of Tier 1 violations, especially nitrate, in rural, low-income areas (*SI Appendix*, Table S4).

Lastly, we assess how bottled water sales may change in response to repeat violations as well as the postviolation period. For repeat violations, we find that repeat violations, both Tier 1 and Tier 2, are associated with a greater increase in sales, relative to the first-time violations (*SI Appendix*, Table S7). This greater response is 16.8 percentage points for repeat Tier 1 violations and 5.8 percentage points for repeat Tier 2 violations. This indicates that the sales response increases over time, perhaps due to learning. Moreover, it alleviates some concern regarding jointness in production, since we do not find a declining response over time, which can be caused by habitual purchase of bottled water. This indicates that the estimated increases in sales during violation events likely are attributable to health-related reasons for bottled water purchase.

Table 3. Estimated effects of quality violations on bottled water sales, by demographic groups

	Rural, low income	Rural, high income	Nonrural, low income	Nonrural, high income
Any Tier 1	0.109	0.287***	0.139**	0.016
	(0.089)	(0.079)	(0.053)	(0.055)
Observations	182,871	93,776	377,724	466,295
Tier 1: Pathogens	0.167**	0.165***	0.137**	0.115***
	(0.076)	(0.061)	(0.053)	(0.028)
Observations	182,871	93,776	377,724	466,295
Tier 1: Nitrate	0.084	0.311***	0.979***	−0.270
	(0.113)	(0.091)	(0.278)	(0.212)
Observations	182,871	93,776	377,724	466,295

Coefficient estimates of β_1 in Eq. **1**, for 4 types of communities, described in *SI Appendix, SI Materials and Methods*; ***significant at the 1% level; **significant at the 5% level. SEs (in parentheses) clustered at county level. All regressions include year, week, and county fixed effects. In addition, regressions control for all variables presented in Eq. **1**. Counties are designated as low-income if household income is below the median of the sample, based on the average income across all years for each county. Counties are classified as rural if average housing density across all years is <16 units per square mile, based on rural categories defined in ref. 22.

In addition, we examine whether bottled water sales remain elevated after a violation period has ended. We find that the postviolation period has slightly higher sales (2.3%) compared to before a Tier 1 violation occurs for the first time in a given county (*SI Appendix*, Table S8). For counties that experience repeat violations, sales are not significantly different from before a first-time violation (*SI Appendix*, Table S8, model 3). When including an interaction term for postviolation period and number of weeks after a violation, we find that elevated postviolation sales slightly decline with greater time after violation (*SI Appendix*, Table S8, model 2).

Discussion

Understanding the scope of community response to impaired drinking water could improve public notification and prioritization of assistance from environmental regulators and public health agencies, both at the state and county level.

Three key findings emerge from this study. First, communities respond to water quality violations by taking averting action, through the purchase of bottled water. Much greater averting action is taken against contaminants that might pose a greater perceived health risk and that require more-immediate public notification. For example, greater increases in sales are found for Tier 1 violations compared with Tier 2. This is likely attributable to customers being more aware of the occurrence of Tier 1 violations and having a strong motivation to take action to avoid immediate health consequences. In addition, violations related to pathogens are associated with significant increase in sales, while other contaminant types are not. This is also likely due to the perceived health risk and content of public notices.

Second, a learning process might occur that causes communities to be more responsive to repeat violations. In particular, for repeat Tier 1 violations, bottled water sales are much higher compared to the first observed violation.

Third, rural, low-income communities are found to not have significant changes in bottled water purchase due to Tier 1 nitrate violations. This is a potential concern due to the higher prevalence of nitrate violations in rural, low-income areas. Nitrate poses a particular risk to infants, and emerging evidence suggests that adults could face greater risk of colorectal cancer and thyroid disease (23). Further research is needed to identify why rural, low-income communities do not tend to purchase bottled water in response to violations that they disproportionately experience. It is unclear whether these communities are not averting exposure at all or whether they are taking alternative protective actions. Future research could also explore averting actions taken by vulnerable groups such as immunocompromised, young children, and elderly populations.

Several policy implications arise from our findings. Tracking consumer purchases could inform response efforts of state and local agencies to emerging water quality concerns, especially those that might be undetected or unreported. An estimated 26 to 38% of SDWA violations are either inaccurately reported or not reported at all to the national EPA (21, 24). Better characterizing the scope of violations is crucial for appropriately prioritizing public health response and guidance to noncompliant water systems. Furthermore, it is critical to inform the public of water quality concerns so that adequate averting action can be taken.

Additional surveillance of drinking-water quality via consumer purchases could be beneficial for water systems and regulatory agencies across the country. This could offer a game-changing way to improve response of state and local agencies to water quality issues and monitor possible public health concerns. Such surveillance could monitor trends over time and determine whether communities are being adversely affected by impaired water quality.

Overall, this study provides insight into how averting behavior differs across violation types and community demographics. Such knowledge can improve understanding of the extent to which communities attempt to reduce exposure to impaired drinking water. This study can inform a more targeted approach to public notification and providing assistance to communities that do not adequately avert exposure to contaminants.

ACKNOWLEDGMENTS. We thank Haowei Wu for excellent research assistance and assembling the county-level climate data. Sales data were obtained from The Nielsen Company (US), LLC. Researchers' own analyses calculated based, in part, on data from The Nielsen Company (US), LLC and marketing databases provided through the Nielsen Datasets at the Kilts Center for Marketing Data Center at The University of Chicago Booth School of Business. The conclusions drawn from the Nielsen data are those of the researchers and do not reflect the views of Nielsen. Nielsen is not responsible for, had no role in, and was not involved in analyzing and preparing the results reported herein.

1. J. Currie, J. G. Zivin, K. Meckel, M. Neidell, W. Schlenker, Something in the water: Contaminated drinking water and infant health. *Can. J. Econ.* **46**, 791–810 (2013).
2. M. Allaire, H. Wu, U. Lall, National trends in drinking water quality violations. *Proc. Natl. Acad. Sci. U.S.A.* **115**, 2078–2083 (2018).
3. J. Rodwan, Bottled water: 2017 staying strong. https://www.bottledwater.org/public/BMC2017_BWR_StatsArticle.pdf. Accessed 17 June 2019.
4. C. Abdalla, B. Roach, D. Epp, Valuing environmental quality changes using averting expenditures: An application to groundwater contamination. *Land Econ.* **68**, 163 (1992).
5. A. Harding, E. Anadu, Consumer response to public notification. *J. Am. Water Works Assoc.* **92**, 32–41 (2000).
6. W. Harrington, A. Krupnick, W. Spofford, *Economics and Episodic Disease: The Benefits of Preventing a Giardiasis Outbreak* (Resources for the Future, Washington, DC, 1991).
7. A. Laughland, W. Musser, J. Shortle, L. Musser, Construct validity of averting cost measures of environmental benefits. *Land Econ.* **72**, 100 (1996).
8. J. Zivin, M. Neidell, W. Schlenker, Water quality violations and avoidance behavior: Evidence from bottled water consumption. *Am. Econ. Rev.* **101**, 448–453 (2011).
9. S. Vedachalam, K. T. Spotte-Smith, S. J. Riha, A meta-analysis of public compliance to boil water advisories. *Water Res.* **94**, 136–145 (2016).
10. M. K. Lindell, J. L. Mumpower, S.-K. Huang, H.-C. Wu, C. D. Samuelson, Exposure path perceptions and protective actions in biological water contamination emergencies. *Environ. Health Insights* **9**, 13–21 (2015).
11. G. Rundblad, The semantics and pragmatics of water notices and the impact on public health. *J. Water Health* **6** (suppl. 1), 77–86 (2008).
12. Z. Hu, L. W. Morton, R. L. Mahler, Bottled water: United States consumers and their perceptions of water quality. *Int. J. Environ. Res. Public Health* **8**, 565–578 (2011).
13. P. Jakus, W. Shaw, T. Nguyen, M. Walker, Risk perceptions of arsenic in tap water and consumption of bottled water. *Water Resour. Res.* **45**, W0540 (2009).
14. D. Wrenn, H. Klaiber, E. Jaenicke, Unconventional shale gas development, risk perceptions, and averting behavior: Evidence from bottled water purchases. *J. Assoc. Environ. Resour. Economists* **3**, 779–817 (2016).
15. Kaiser Family Foundation, "Kaiser health tracking poll: April 2016" (#8868-T, Kaiser Family Foundation, Menlo Park, CA, 2016).
16. T. Scherzer, J. C. Barker, H. Pollick, J. A. Weintraub, Water consumption beliefs and practices in a rural Latino community: Implications for fluoridation. *J. Public Health Dent.* **70**, 337–343 (2010).
17. Government Accountability Office, "Consumers often not well-informed of potentially serious violations" (GAO/RCED-92-135, Government Accountability Office, Washington, DC, 1992).
18. Environmental Protection Agency, "Revised public notification handbook" (EPA 816-R-09-013, Office of Water, Washington, DC, 2010).
19. Environmental Protection Agency, Public notification of drinking water violations. *Code of Federal Regulations*. https://www.govinfo.gov/app/details/CFR-2010-title40-vol22/CFR-2010-title40-vol22-part141-subpartQ/summary. Accessed 21 August 2019.
20. Environmental Protection Agency, "Water health series: Bottled water basics" (EPA 816-K-05–003, Environmental Protection Agency, Washington, DC, 2005).
21. Environmental Protection Agency, "Data reliability analysis of the EPA safe drinking water information system/federal version (SDWIS/FED)" (EPA 816-R-00-020, Office of Water, Washington, DC, 2002).
22. I. Leinwand, D. Theobald, J. Mitchell, Landscape dynamics at the public-private interface: A case study in Colorado. *Landsc. Urban Plan.* **97**, 182–193 (2010).
23. M. H. Ward *et al.*, Drinking water nitrate and human health: An updated review. *Int. J. Environ. Res. Public Health* **15**, E1557 (2018).
24. Government Accountability Office, "Drinking water: Compliance problems undermine EPA program as new challenges emerge" (GAO/RCED-90-127, Government Accountability Office, Washington, DC, 1990).