The Costs of Nitrate Pollution in Drinking Water*

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Abstract

Nitrate contamination of drinking water is a widespread and worsening environmental concern. The magnitude of the environmental health consequences depend on an individual's ability to avoid exposure. However, there are a number of factors which may undermine one's ability to avoid pollution exposure. This paper studies the heterogeneity in avoidance behavior following Safe Drinking Water Act nitrate violations. I find that consumers exhibit averting response through both bottled water and sugar sweetened beverages. However, consumers in food deserts show a 31 percentage points lower response relative to consumers with supermarket and grocery access. These results are informative to the mechanisms through which individuals are persistently exposed to environmental pollution despite the presence of regulation.

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1 Introduction

Nitrate pollution exposure through drinking water poses significant health threat and is a widespread and worsening issue. Excessive levels of ingested nitrates pose an acute health risk to infant – being a well-known cause of "Blue-Baby Syndrome" (or methemoglobinemia) – potentially resulting in death (Walton, 1951). Rural areas are especially vulnerable with nitrogen-intensive agricultural production to nitrate pollution (Metaxoglou and Smith, 2022). The extent of these health damages largely depends on individual's ability to adapt to the environmental hazard

Many environmental regulations are conceptualized around the assumption that those exposed to pollution have the ability to avoid the negative externality once information about the local environmental hazard is revealed. The Safe Drinking Water Act (SDWA) uses information disclosures and public notices to alert consumers of drinking water quality violations and mitigate the risks to public health. However, Marcus (2021) and others show that consumers respond to water quality information heterogeneously.[1]

A variety of constraining factors may limit avoidance pollution avoidance. These factors may be particularly acute in rural areas, where residents disproportionately experience SDWA nitrate violations, often due to agricultural pollution (Allaire, Wu, and Lall, 2018; Paudel and Crago, 2020). Income constraints, market accessibility, and other infrastructure gaps may limit rural residents' ability to protect themselves from drinking water pollution. (De Janvry, Sadoulet, and Murgai, 2002). Greenstone and Jack (2015) hypothesize that marginal willingness to pay for environmental goods is often low in developing country settings due to low incomes and high marginal costs of environmental quality improvement. These factors may similarly lead to small measures of marginal willingness to pay for drinking water quality in the rural United States, where quality improvements should be valuable because of the high rates of violations.

The objectives of this paper are to evaluate the distribution of avoidance behavior as

[1]Also see (Zivin, Neidell, and Schlenker, 2011) and (Allaire et al., 2019).

measured by bottled water purchases and other beverage sales, the mechanisms underpinning heterogeneity in avoidance behavior, and the effects of on human health. I estimate the extent to which differences in demographics and grocery store accessibility may limit some populations' ability to avoid consuming nitrate contaminated drinking water more than others. In doing so, this paper contributes to our understanding of the mechanisms behind lower marginal willingness to pay for drinking water quality in some populations, advances the environmental justice narrative by accentuating the constraints impacting vulnerable communities, and offers insight on the most effective means of environmental regulation in resource-constrained areas.

My conceptual model builds on Harrington and Portney (1987) and others to observe marginal willingness to pay through avoidance behavior. I modify this model to allow individuals to face differential implicit prices to averting behavior. These unique implicit prices may arise from geographic resource constraints. The analytical results from this model predict that individual facing higher implicit prices will engage in less averting behavior, leaving some populations differentially exposed to pollution.

Income, lack of news coverage, and grocery accessibility constraints – which are all particularly relevant to residents in the rural United States – may limit consumers' ability to avoid contaminated drinking water. If the public notification successfully induces avoidance, I anticipate that health outcomes improve or remain unchanged after protection. However, limited protective behavior may cause health outcomes to be unaffected or only modestly improved after public notification, which would imply that the information alone may not be sufficient to address the full spectrum of factors causing environmental health impacts, especially for constrained populations. I test these theoretical hypotheses with my empirical framework.

I study this question in the context of nitrate pollution in drinking water in the US. All public drinking water systems that serve over 25 people are required to maintain reporting, monitoring, and minimum standards of drinking water quality through the SDWA. The

SDWA serves both to ensure local PWS compliance and to notify citizens of the possibility of harmful exposure. Throughout this paper, I assume that the introduction of these SDWA public notifications function as exogenous information shocks since residents often have limited prior information regarding local water quality (Keiser and Shapiro, 2018). [2] Public notifications for SDWA quality violations directs consumer to avoid tap water consumption from the PWS by purchasing bottled water if their marginal utility of clean drinking water is greater than the marginal cost.

I use data from the Safe Drinking Water Information Systems (SDWIS) through the Environmental Protection Agency (EPA) on public water system (PWS) characteristics and violation and enforcement data from 2010-2020. These data report the date of public notification and the subsequent return to compliance for SDWA contaminant rules.[3] I pair these violation and quality records with retail scanner data from Information Resources Inc (IRI) for retail stores across the United States from 2010-2019. IRI retail scanner data contain precise store locations and are the most comprehensive retail data available. Additionally, I utilize food accessibility statistics from the Food Access Research Atlas provided by United States Department of Agriculture Economic Research Service (USDA-ERS) to determine census-block level access to retail grocery stores. I also pair data on local news coverage regarding SDWA public notification from Access World News.

I empirically test the hypotheses of this paper through two stages. First, I estimate the effect of different water quality violation types and subsequent public notification on avoidance behavior through beverage purchases – disaggregated into bottled water sales and – using an event study framework. The main outcome of interest is the value of logged bottled water sales (in cents) at the store-week level. Store and week fixed effects control

[2]This assumption may be too restrictive for some violation types, but the estimates provide a lower bound in these cases.Some violations, like Total Coliform (TCR), may be more likely and anticipated around predicted weather events, like hurricanes. In this event, bottled water sales may already be high in pre-violation weeks in anticipation of the weather event (Beatty, Shimshack, and Volpe, 2019). Therefore, the observed treatment effect would be biased towards zero.

[3]In a sub-sample of states, I also observe water quality directly, which helps disentangle the relationship between water quality and consumer behavior from public notification. However, SDWIS does not systematically report all

for fixed differences across stores and seasonality in bottled water sales. In the baseline specification, I consider a store and week as "treated" if the observation falls between the public notification date and the return to compliance date. The event study framework then helps uncover the short and longer-run avoidance response. The main coefficients of interest can be interpreted as the percent increase in bottled water sales for each event-week following the notification relative to the store and calendar week's expected outcome in the absence of a violation. This percent increase is the value of protection to residents served by contaminated water systems.

I also allow for heterogeneity in the estimates of avoidance behavior by census tract through measures of income, percent of population in food deserts, SNAP participation, and vehicle access. This analysis highlights factors that may leave vulnerable populations exposed even after SDWA public notification.

This paper most closely relates to the works of Zivin, Neidell, and Schlenker (2011) and most recently, Allaire et al. (2019), who also measure marginal willingness to pay based on SDWA public notices and bottled water sales. The baseline estimates I receive for marginal willingness to pay fall within the confidence interval of these previous studies. I extend these works to study how these estimates of marginal willingness to pay may be attenuated to zero due to income, grocery-accessibility, or other resource constraints. In part, I also contribute to the wide body of literature that studies the effectiveness of the SDWA (Bennear and Olmstead, 2008; Bennear, Jessoe, and Olmstead, 2009).

I find evidence of significant avoidance behavior through bottled water purchases for nitrate contaminant violations. Public notifications due to nitrates induce between an approximate 17% increase in bottled water sales and 11% in sugar sweetened beverages in the weeks following notification. This translates roughly to $4.7 million annually in averting expenditures due to nitrate contamination - a relatively inexpensive form of protection for those with access.

Food accessibility and income constraints significantly limit avoidance through beverage sales by 31 and 26 percentage points, respectively, illustrating the implicitly higher barrier these residents face to avoid contaminated water (or access costs are elevated) compared to residents with proximate grocery access.

These findings will result in three relevant policy conclusions. First, studies that estimate willingness to pay using avoidance behavior may significantly underestimate the impact if other factors limit avoidance. That is, consumers with resource constraints may highly value environmental improvement, but only small responses may be observed in observational data due to barriers to averting behavior. Second, current regulatory measures that aim to protect citizens from drinking water pollution may be ineffective in resource constrained areas; in the future, these areas may need a multifaceted policy approach, like ensuring those affected have the opportunity for a safe alternative, to lessen damages to public health. Lastly, policy measures that are ineffective in some populations may leave vulnerable communities continually exposed to environmental health impacts, worsening environmental inequality.

2 Background

SDWA

The SDWA, initially passed in 1974, regulates drinking water systems that serve at least 25 individuals and aims to protect individuals drinking water pollution or waterborne illness. It requires regular monitoring and reporting of drinking water quality by systems and establishes maximum contaminant levels (MCL) for over 90 contaminants. Some contaminants are short-lived and quickly treatable in-home, while others are legacy pollutants and are costly to rectify by households or public water systems. MCLs are determined by the threshold which contaminants pose a potential health threat to certain populations.

Once a violation occurs, the SDWA relies on public notifications to alleviate the public health risk. The public notification requirements establish 3 tiers. Tier 1 violations pose immediate threat to human health and notification must occur within 24 hrs of detecting contaminants above the MCL. Nitrates and some violations of the Total Coliform Rule are the two contaminants that are classified as Tier 1 violations. These notices are required to hand delivered, published in local news outlets, and posted in public areas based on these tiers. An example of a Tier 1 public notification and the required elements is provided in figure 6. Tier 2 violations include arsenic, lead, copper, among others. Tier 3 violations are often do to reporting or monitoring failures. Notification must occur within 30 days and 365 days, respectively, for tier 2 and 3 violations.

SDWA violations and subsequent notifications have been widely used in economic studies as exogenous treatment in quasi-experimental settings (Bennear and Olmstead, 2008; Zivin, Neidell, and Schlenker, 2011; Allaire et al., 2019). Most recently, Marcus (2020) utilizes the variation in public notification tiers to identify health and averting behavior for TCR violations in North Carolina. Similarly, this paper uses SDWA public notification to study the mechanisms through which notification-based environmental regulation yields limited response in some populations and the related health costs.

Figure 1 plots the spatial variation in nitrate violations by county in the US from 2010-2019. Larger numbers of violations happen in the Great Plains and the West.[4] This pattern also loosely follows the spatial variation of farm nitrogen application in the US, discussed in the next section.

Nitrate Contamination & Health Impacts

The EPA describes nitrogen pollution of the US's most widespread and costly forms of environmental pollution. While this pollution is the result of a number of anthropogenic activities, agriculture is the primary contributor of this pollution. In the United States, agricultural fertilization accounted for approximately 93% of commercial nitrogen use in

[4]This relationship also coincides with a greater dependency on groundwater as approximately 95% of all nitrate violations are sourced from groundwater Pennino, Compton, and Leibowitz (2017). A heavy concentration of violations through Texas, Oklahoma and Kansas closely follow the boundaries of the Ogallala Aquifer. The same is true in California's central valley.

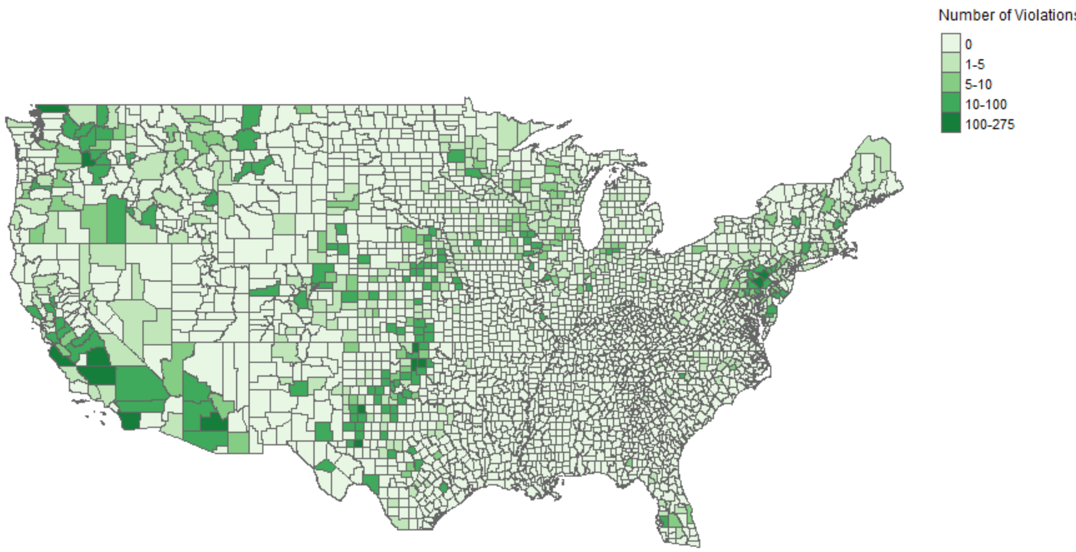

Figure 1: Number of SDWA Nitrate Violations, 2010-2019

2010.[5] Figure 2 plots 2010 agricultural nitrogen use by county. Unsurprisingly, the most heavily concentrated areas span across the Corn Belt and in California's central valley.

Global use of agricultural nitrogen fertilizer has steadily risen over the last century (FAO, 2020). This trend is, in part, driven by an increasing global population and demand for food. In the last two decades, expanded use of biofuels due to the Renewable Fuel Standard resulted in additional demand for fertilizer (Lark et al., 2022). Advances in production technology (i.e. the Haber Bosh process) in the early 20th century and low energy prices also contributed to increased fertilizer use from the supply side.

Assessing the scope of the environmental costs of nitrogen use is a multi-disciplinary task and remains a challenge for economic researchers (Keiser, Kling, and Phaneuf, 2020). Nitrogen contamination in surface waste and associated environmental harm manifests primarily through algal blooms (Hendricks et al., 2014). Algal blooms create dead zones (or hypoxic zones) in bodies of surface water, which are detrimental to aquatic life and costly

[5] Authors calculations from John and Gronberg (2017)

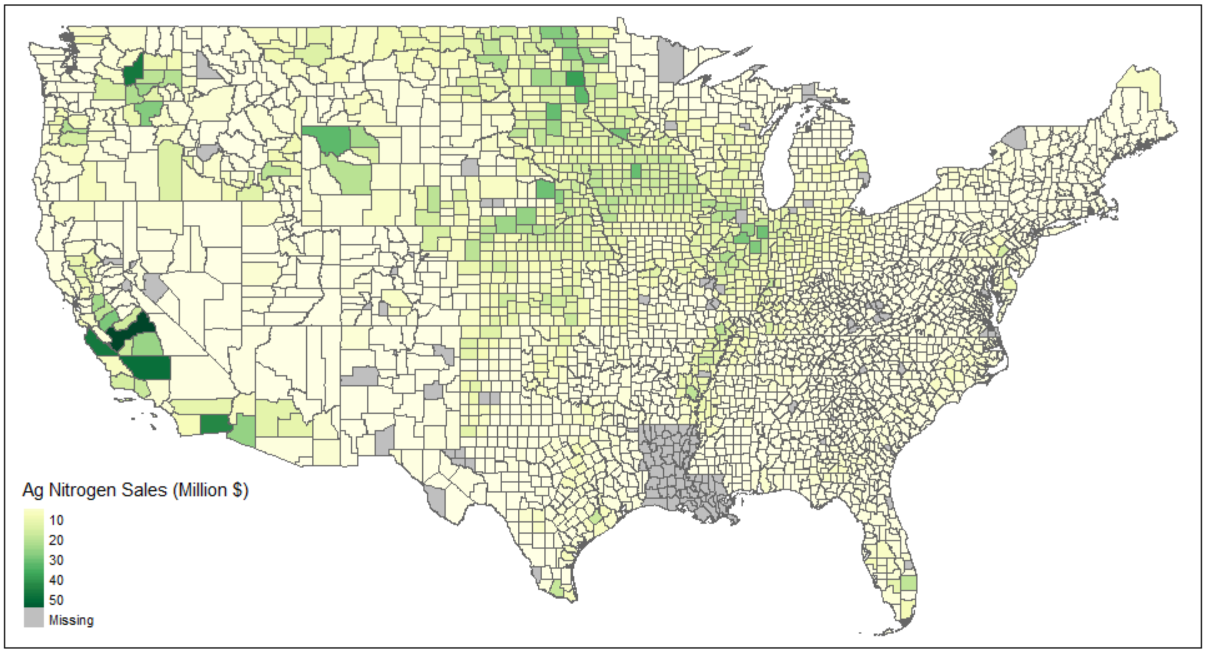

Figure 2: Agricultural Nitrogen use by County, 2010

to human recreation (Egan et al., 2009). Tracking non-point source nitrogen pollution in surface water remains an active field of research (Paudel and Crago, 2020; Taylor and Heal, 2022).

Nitrates in groundwater are an irreversible pollutant and often require households or water suppliers to identify new sources once detected. Approximately 90% of rural residents in the US rely on groundwater for domestic use (Power and Schepers, 1989). PWS that source from groundwater account for 95% the historical SDWA violations (Pennino, Compton, and Leibowitz, 2017).[6] Nitrates are leached through the soil into groundwater basins over time, so the full externality is not realized until many years, even decades, after the polluting activity (Harter et al., 2012). Unlike bacterial contaminants, boiling the water does not eliminate the concentration and the long-term solutions are costly to the public water system. Once a groundwater source is contaminated with nitrates, contamination levels persist – they are

[6]This does not include households that rely on private wells for domestic use. Private groundwater wells are perhaps even greater risk of environmental harm since these wells are outside the jurisdiction of the SDWA and do not require regular monitoring.

unlikely to decline. Thus, public water systems must identify new sources of water, which are also susceptible to contamination, or build an expensive water treatment plant.[7]

Exposure to nitrates pose the highest health risk for infants and pregnant mothers. High levels of nitrate exposure is correlated with an increased risk of Methemoglobinemia (or blue-baby syndrome), which limits adequate oxygenation of the blood. The 10 mg/L MCL threshold set by the EPA is based on a 1951 survey, which identified 2.3 percent of Methemoglobinemia cases were associated with nitrate concentrations above 10 mg/L (Walton, 1951). The World Health Organization shares this same guideline internationally.

Constraints to Averting Response

A number of economic factors may limit an individual's ability to respond to information about environmental quality. These factors lead to smaller observed marginal willingness to pay (MWTP) for environmental improvement. However, estimates of MWTP in the presence of significant constraints underestimates the true MWTP. The lack of reliable new outlets in an area, for example, leads to a dampened local response to public notifications of pollution (Marcus, 2021). However, the same individuals may chose a meaningfully different response in the presence of broadly communicated information about pollution to a population. Policy aimed at limiting pollution exposure must also carefully consider these constraints that may vary across populations.

This study highlights the interaction between food deserts and SDWA nitrate violation, two realities that are acute in the rural US (Bitler and Haider, 2010). Generally, food and beverage items have higher retail prices in food deserts due to higher operating costs. Residents living in food deserts also face higher access costs through travelling longer distances to travel to a supermarket. The presence of food deserts and their implication inequality and nutrition have long been debated (Allcott et al., 2019).

For this paper, I use USDA's definition of a food desert (or low access) as a census

[7] Anecdotal evidence suggest industrial water treatment cost upwards of of $3 million, and require additional year-to-year operational costs.

tract with at least 500 people, or 33 percent of the population, living more than 1 mile in urban or more than 10 miles in rural areas from the nearest supermarket, supercenter, or large grocery store.[8] Figure 3 plots rural food deserts in the US. Again, rural food deserts are highly prevalent in the Western US. Tables 5 and 6 show that food deserts and rural areas both face higher prices for bottled water and sugar sweetened beverages, respectively.

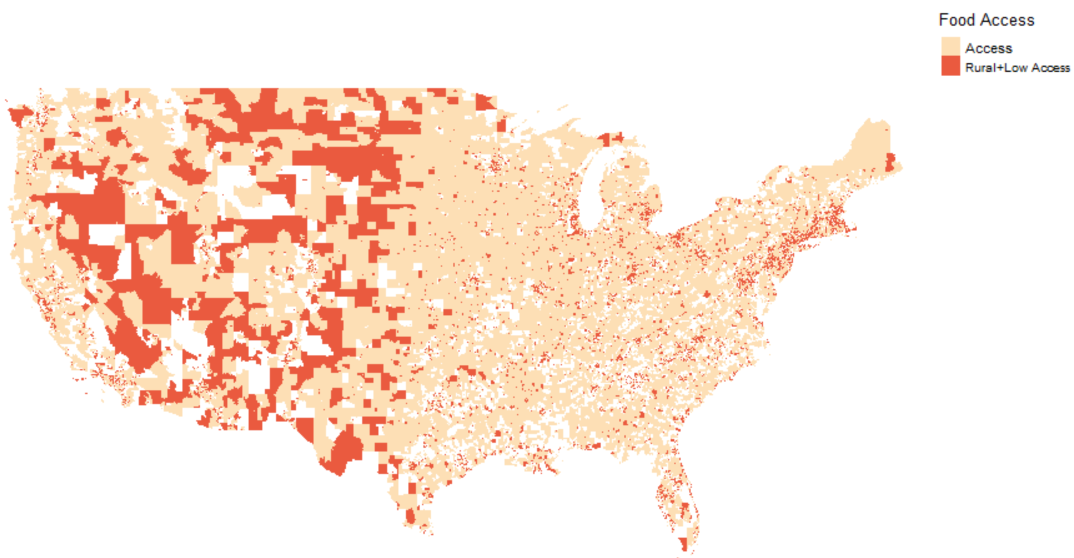

Figure 3: Low Grocery Access Census Tracts, 2015

3 Conceptual Model

I develop a stylized conceptual framework to illustrate how resource constraints may limit averting behavior. Consumers derive utility from health, H, and a composite good, X. Health is a function of the pollutant, T and protecting behavior, B. In the context of this paper, T is tap water contamination, and B is an safe alternative beverage. Health is decreasing in environmental pollution, $H_T < 0$. Other beverages provide a safe source of

[8] Following USDA's Food Research Atlas.

water consumption, $H_B = 0$.[9]

$$\begin{aligned} U &= U(H, X) \\ H &= H(T, B) \end{aligned} \tag{1}$$

Consumers maximize utility subject to a budget constraint, Y. I follow Abrahams, Hubbell, and Jordan (2000) and assume that the price of tap water is equal to zero, and denote the price of purchasing beverages at retail by p_B. However, each consumer must also experience an unique implicit price, $p_I^i \geq 0$, in order to obtain the safe beverage source. For the context of this paper, implicit prices arise due to limited accessibility. The price of the composite good is normalized to 1 and utility is monotonically increasing in the composite good. Therefore, the consumer solves the utility maximization problem:

$$\max_B \; U(H(T, B), Y - (p_I^i + p_B)B) \;\; \text{s.t.} \qquad B \geq 0 \; [\mu] \tag{2}$$

This utility maximization problem yields the following set of first order conditions:

$$\begin{aligned} & U_H H_B - U_X(p_I^i + p_B) + \mu = 0 \\ & \mu B = 0 \\ & \mu \geq 0 \end{aligned} \tag{3}$$

Two relevant cases emerge from these conditions.

Case 1: $(B = 0)$

Under this scenario, consumers utilize only tap water for their residential and drinking needs. For a corner solution to exist for other beverage consumption the inequality in

[9] This assumption could conceivably be violated if excessive consumption of the alternative beverage source is detrimental to health, like soda or alcohol. While this question is studied with the empirical model, it is beyond the scope of this stylized framework.

equation (4) must hold, where the right-hand side represents the shadow value of avoiding health damages from tap water consumption. The corner solution emerges when the marginal rate of substitution between the composite good and health is greater than the shadow price of perceived health damages. Equation (4) implies that either (i) the perceived damages from drinking tap water are sufficiently small and (ii) that the price of alternative beverages are sufficiently high relative to the marginal utility of the composite good, X, so that the consumer chooses to not purchase other beverages.

$$\frac{U_X}{U_H} > \frac{-H_T}{p_I^i + p_B} \tag{4}$$

Case 2: $(B > 0)$

In case 2, the consumer purchases a positive amount of the alternative source. Demand for B will satisfy equation (5) and will be a function of the exogenous water quality (T), income (Y), the retail price (p_B), and the unique implicit price faced by each consumer, (p_I^i). This equation represents the tradeoff between investing in additional units of a clean source of drinking water and the composite good.

$$\frac{U_X}{U_H} = \frac{-H_T}{p_I^i + p_B} \tag{5}$$

An exogenous change in T will yield a non-negative change in demand for safe beverages, represented by the partial $\frac{\partial B}{\partial T}(Y, p_I^i + p_B)$. Traditionally, this change in protective behavior reflects the marginal willingness to pay to avoid pollution. Econometric specifications estimate this reduced-form change in demand for an exogenous environmental quality change. However, this ignores the implicit costs consumers face, leading traditional estimates to underestimate the full valuation of environmental quality. High implicit costs, p_I^i, may contribute to why the valuation for environmental goods has been found to be lower in developing country setting.

Bottled water and other beverages for residents in food deserts in rural areas may be relatively more expensive due to either higher transportation costs or higher baseline retail prices. Grocery access in food deserts increases the cost for consumers to substitute bottled water for tap water consumption. Holding all other factors constant, I hypothesize that averting behavior is dampened in food deserts due to the interaction of costly grocery access in rural areas. I measure this effect by interacting food access statistics with the public notification information shock.

Consumers in food deserts also may be less likely to consume bottled water due to a higher retail price in the local retail stores. As the price of bottled water increases in equation (4), the necessary marginal utility of the composite good for a corner solution becomes smaller. Hence, even in the event of a positive shock to T, the shadow value remains small enough for consumers to stay at the corner solution.

4 Data

SDWA violations and subsequent notifications provide a quasi-experimental context to study averting behavior. This research design assumes that consumers cannot predict an impending SDWA violations and that notification serves as an exogenous shock to perceived water quality. I provide evidence that consumers only respond in the weeks after a violation occurs, not prior, which supports the exogeneity of this design. To measure averting response heterogeneity, I assemble a store-by-week panel from 2010-2019. I exploit weekly within-store variation SDWA nitrate violation events to identify average treatment effects and observe cross-sectional heterogeneity across resource constraints.

Water Quality Violations

Enforcement and Compliance History Online (ECHO) through the EPA contains a record of SDWA violations and enforcement actions for PWS across the United States. To ensure a precisely identified exogenous shock to perceived water quality, I use tier 1 public notifications from SDWA nitrate violations and notifications as the main sample for my estimation strategy.[10] Throughout the remainder of the paper, I use the terms violations and notifications interchangeably since the events occur on the same day for tier 1 violations.

I define that treatment occurs in the weeks between the date of public notification to the return to compliance date. Figure 7 illustrates the timing of these occurrences throughout the year, showing that some violation types are more seasonal than others.

Beverage Sales

Beverage sales data come from Information Resources Inc (IRI), which provide the most geographically comprehensive scanner data available. These retail scanner data cover over 48,000 stores nationally and measure weekly sales by product code (UPC). The widespread coverage of this data is particularly helpful in measuring the impacts in rural areas, where data availability is typically sparse. I disaggregate beverage sales into two categories: bottled water and sugar sweetened beverages. Each measure is the sum of weekly store revenue from all types of bottled water or sugar sweetened beverages. These data are reported for a variety of store types as exhibited in Figure 8.

Grocery Access & Demographics

The Food Access Research Atlas from the USDA provides cross-sectional census-tract level food access statistics determined by the distance to the nearest grocery store or source of healthy food. The Food Access Research Atlas also contains characteristics that may limit food access, like income and vehicle ownership. This dataset is primarily derived from the 2010 Census, the 2014-2018 American Community Survey, and the 2019 STARS (Store Tracking and Redemption System). These data provide the primary community characteristics through which I evaluate heterogeneity in averting behavior.

[10]While the public notification date is included in the data, leakages of information or slow dissemination of water quality information may happen between the violation date and the public notification. This possibility threatens the experiment design and may lead to an anticipation effect.

Given that these data are cross-sectional, they will be unable to capture any variation in demographics over the course of the sample. For example, water pollution may cause local residents to move to reduce exposure to the pollutant – a more long-run and extreme form averting behavior. However, given that this type of out-migration could take years to be fully realized, this possibility is unlikely to bias the short-run averting response through beverage sales.

5 Empirical Model

Averting Behavior and Heterogeneity

The staggered nature of SDWA violations in communities across the United States allows for the implementation of a dynamic difference-in-difference (DD) empirical specification. A number of studies have similarly used the exogenous and staggered timing of SDWA violations as a quasi-experimental research design. However, a large and growing literature documents the potential bias in difference-in-difference estimated using two-way fixed effects (TWFE) with variation in treatment timing (Goodman-Bacon, 2021). Generally, TWFE controls time-invariant differences and macroeconomic shocks. However, the bias arises because TWFE also residualizes the treatment variable, and already treated units are used as implicit counterfactuals. The magnitude of the TWFE bias is dependant on the degree of heterogeneity across time and has potentially serve consequences of the interpretation of TWFE coefficients.

While this potential bias is now well understood, subsequent work has proposed alternative estimators to TWFE to uncover unbiased estimates in staggered DD settings (Callaway and Sant'Anna, 2019; Gardner, 2021). For this setting, Gardner (2021) provides an ideal estimator, estimating DD estimates in two-stages. Using only pre-treated units, the time and individual fixed effects are estimated in the first stage. The remaining variation in the outcome variable, after controlling for fixed effects, is used to identify the unbiased treatment effect in the second stage. I demonstrate this small bias by comparing the TWFE estimates, which are similar to (Allaire et al., 2019), with the estimator from Gardner (2021).

To estimate the response to tier 1 SDWA public notifications, I estimate equation (6), where B_{ist} are beverage sales in cents at store i and in state s in week-year t. Treatment, Vio_{ist} is equal to 1 during active violation weeks, and 0 otherwise. I multiply treatment by w_i, which is the percentage of the store's census-tract affected by the violation. Together, $Vio_{ist} * w_i$ capture the community treatment intensity. The vector $\boldsymbol{X_{iwt}}$ captures time-varying controls (e.g., weather). The base specification uses week by year fixed effects denoted by λ_t, which absorbs national seasonality in beverage sales and macroeconomic shocks. I also include store-by-event fixed effects, α_i, which capture time-invariant factors, like store location and size of the consumer population.[11] Additionally, state-by-year fixed effects, ϕ_s, capture state-year specific regulatory differences.[12] Standard errors are multi-clustered at the store and violation level (Cameron, Gelbach, and Miller, 2011). This accounts for potential serial correlation within individual stores over time and between stores affected by the same violation. Following Gardner (2021), I estimate equation 6.

$$\begin{gathered}\textit{With not yet treated sample: } \log(B_{ist}) = \boldsymbol{\phi' X}_{ist} + \lambda_t + \alpha_i + \phi_s + \varepsilon_{ist} \\ \textit{With full sample: } \hat{\varepsilon_{ist}} = \beta Vio_{ist} * w_i + \boldsymbol{\phi' X}_{ist} + \mu_{ist}\end{gathered} \tag{6}$$

I additionally estimate the dynamic version (or event study) of equation 7 to offer insight into the evolution of the treatment effect in the weeks following a violation and detect persisting effects beyond a return to compliance. This specification also allows a test of the identifying assumption that, conditional on fixed effects and covariates, beverage purchases

[11] Population size and demographics of the local population could obviously change over the course of the panel. This change is a potential omitted variable if it correlated with treatment timing (i.e. out-migration due to poor water quality). This implies that our point estimates underestimate the full averting behavior taken by consumers, but estimating the out-migration effect is beyond the scope of this paper.

[12] State agencies carry out the enforcement and monitoring of SDWA requirements among PWS.

would have not significantly differed in the absence of violation. Parallel pre-treatment trends in the weeks leading up to a violation supports this assumption. For the event study, I use an eight week window before and after the violation.[13] I ensure a balanced panel during throughout the event study window. Following Schmidheiny and Siegloch, I bin all other observations outside the event study window into the window endpoints. I use the third week prior to violation as the baseline week, which allows this specification to detect any anticipatory effect in the two prior weeks.

The event study results are estimated with equation 7, where $Week_{iw} = 1$ if a store i is w weeks away from the violation. I also interact this event-week dummy with Vio_{iswt} because PWS return to compliance at different points post-violation. Therefore, a PWS that returns to compliance a seven weeks post-violation may yield a more lasting response than a PWS with only a week-long violation. This specification tests for the differing effects between post-violation and compliant versus post-violation with an active violation.

$$\begin{gathered}\textit{With not yet treated sample: } \log(B_{iswt}) = \boldsymbol{\phi' X}_{iswt} + \lambda_t + \alpha_i + \phi_s + \varepsilon_{iswt} \\ \textit{With full sample: } \hat{\varepsilon_{iwt}} = \sum_{w=-8}^{w=8} \beta_{1w} Week_{iw} + \sum_{w=-8}^{w=8} \beta_{2w} Week_{iw} * Vio_{iswt} + \boldsymbol{\phi' X}_{iswt} + \mu_{iswt}\end{gathered} \tag{7}$$

The primary identifying assumption of the event study framework requires parallel trends in the pre-treatment periods. In equation (7), this assumption is supported if β_w for $w \in [-8, -1]$ is not statistically distinguishable from zero.

To test for heterogeneity by community demographics, I will estimate equation (8), which interacts the violation and the public notification dummy variable with cross-sectional characteristics. The vector $\boldsymbol{Z_i}$ contains demographic variables for socio-economic indicators or resource access measures. These measures are time-invariant and are absorbed into the store-by-violation fixed effect when not interacted with treatment. Elements of $\boldsymbol{\gamma}$ will report

[13] Eight weeks is chosen as the window since all nitrate violations in the sample are resolved in 7 weeks or prior of initial violation.

the difference relative to β across values of $\boldsymbol{Z_i}$.

$$\begin{aligned} &\textit{With not yet treated sample: } \log(B_{ist}) = \boldsymbol{\phi' X}_{ist} + \lambda_t + \alpha_i + \varepsilon_{ist} \\ &\textit{With full sample: } \hat{\varepsilon_{ist}} = \beta Vio_{ist} * w_i + \boldsymbol{\gamma Z_i} * Vio_{ist} * w_i + \boldsymbol{\phi' X}_{ist} + \mu_{ist} \end{aligned} \tag{8}$$

6 Results

Bottled Water

For the baseline estimates of averting behavior, I disaggretate beverage sales into bottle water sales – the traditional measure of averting behavior in averting behavior studies – and sugar sweetened beverage. For nitrate violations, bottled water is the recommended alternative source included in public notifications. Boiling water, for example, does not eliminate nitrates and potentially makes nitrates more concentrated. One alternative in-home treatment method that removes nitrates from water is a costly water-treatment system. Purchasing one of these systems reflects a long-run response since it would protect against all future potential water quality risks. Therefore, bottled water sales capture the short-run, lower-bound of averting response by consumers.

Figure 4 displays the dynamic response of bottled water sales for the weeks around nitrate violations. The parallel trends assumption is supported since no pre-treatment week (or binned pre-treatment) is significantly different than the baseline week (i.e. three weeks prior to violation). Positive averting response occurs for active violation the 2nd thru the 7th weeks after the initial violation. This delayed response is suggestive of slow dissemination of information throughout a community. There does not appear to be a persistent effect after water systems return to compliance.

Table 1 displays the results of the average treatment effect across all active violation weeks. Columns (1) and (2) report the biased estimates from TWFE. These point estimates are similar to those of Allaire et al. (2019), suggesting that my sample doesn't differ in a

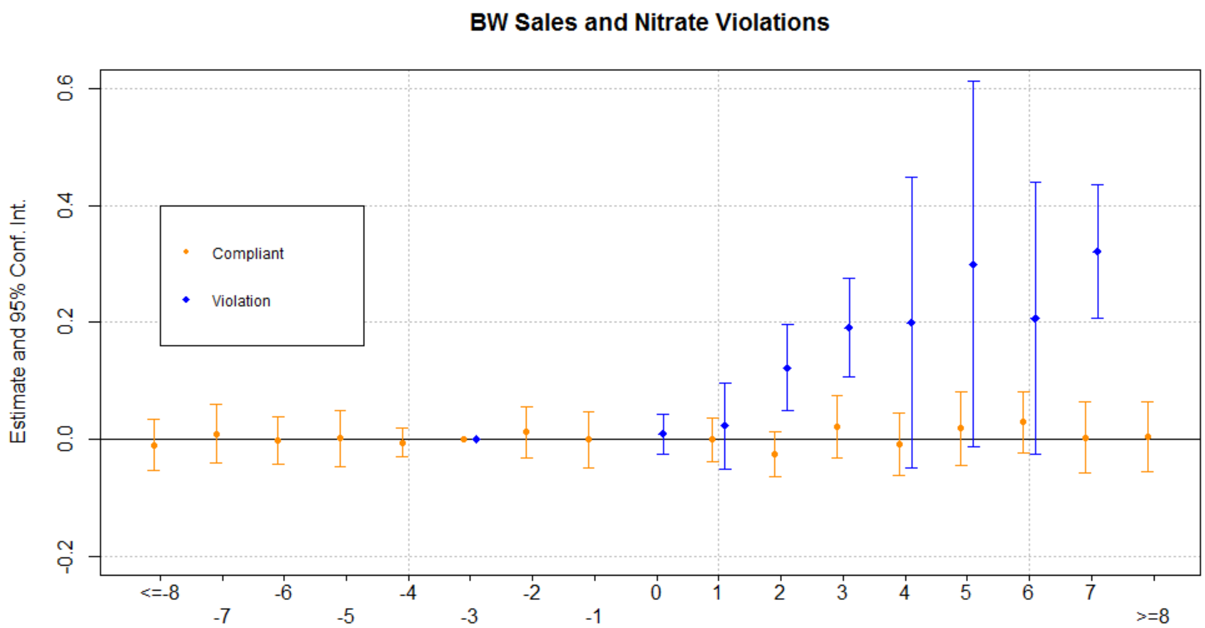

Figure 4: Event Study Results: Bottled Water Sales Pre- and Post- SDWA Violation

statistically meaningful way. Columns (3) and (4) report the two stage DD results from Gardner (2021) and an intention-to-treat effect of 17.3%. In this context, the TWFE does bias the point estimate to zero, but the bias is economically small.

A back of the envelop calculation implies that individuals spend approximately $2.5 million on bottled water purchases annually in the US as a result of nitrate violations. This figure is similar to that of Zivin, Neidell, and Schlenker (2011). To compute this figure, I use national statistics on bottled water sales and nitrate violation statistics from Pennino et al. (2020). This number understates the full amount that individuals spend on averting actions as a result of nitrate violations due to a number of other, long-term protective actions, like water filtration systems. However, bottled water provides a relatively inexpensive alternative for protection against the potentially harmful health effect. Furthermore, I show that this averting response differs across resource constraints and demographics, which may result in some populations remaining exposed to nitrate pollutants.

	log(Bottled Water)			
	TWFE	TWFE	DiD2s	DiD2s
Nitrate Vio x w_i	0.229*	0.128*	0.315*	0.173***
	(0.112)	(0.055)	(0.125)	(0.032)
log(price)	−0.586***	−0.575***	0.018	0.009
	(0.037)	(0.035)	(0.026)	(0.020)
Max Temp		0.016***		−0.001
		(0.002)		(0.003)
Min Temp		0.006*		0.001
		(0.003)		(0.004)
Precipitation		0.000*		0.000
		(0.000)		(0.000)
Num.Obs.	721 897	721 897	614 478	614 478
Std.Errors	Store & Vio	Store & Vio	Store & Vio	Store & Vio
FE: State by Year	X	X	X	X
FE: Store by Event	X	X	X	X
FE: Week by Year	X	X	X	X

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table 1: Bottled Water Sales during SDWA Nitrate Violation

Sugar Sweetened Beverages

Instead of substituting bottled water, some consumers may substitute contaminated tap water with other beverage options, like sugar sweetened beverages (SSB). SSB sales are an alternative form of averting behavior and should not be ignored in calculating the the full response from exogenous changes in nitrate contamination in drinking water. Analysis of SSBs additionally gives insight into the indirect effects of drinking water pollution, as consumers may substitute to beverage options that have their own set of health externalities.

Figure 5 present the event study results, where the outcome are sales of SSB. Again, the parallel trends assumption prior to a violation holds. Similar to bottled water, SSB sales generally increase as a result of active nitrate violations. These coefficients are dampened relative to bottled water, but consumers do respond through alternative beverage forms

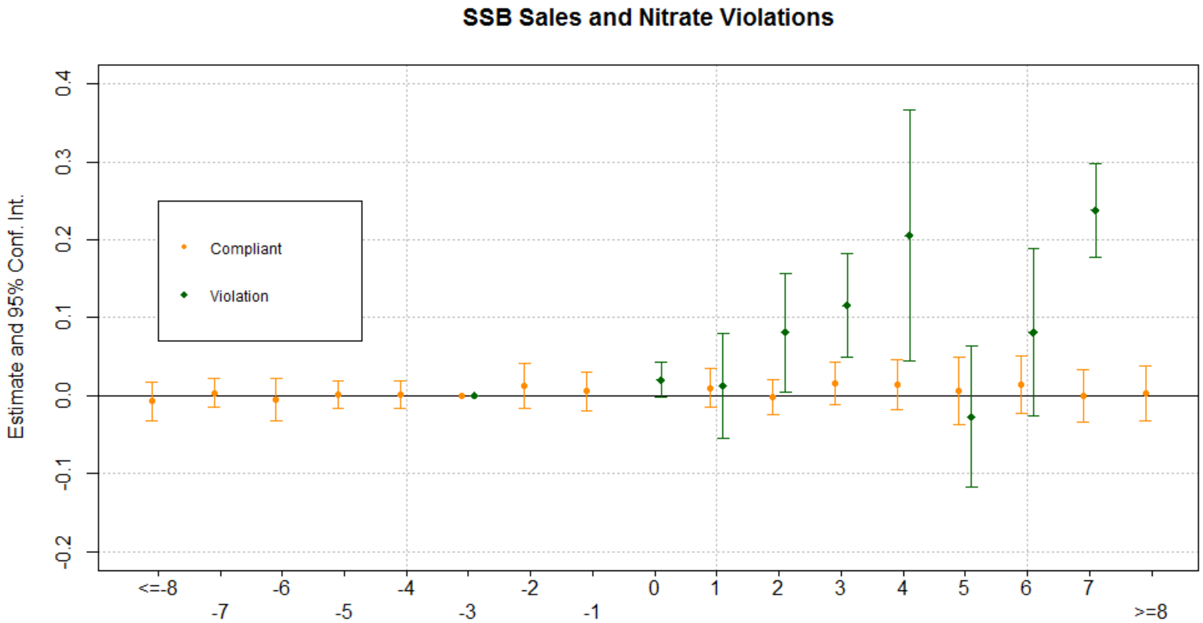

Figure 5: Event Study Results: Sugar Sweetened Beverage Sales Pre- and Post- SDWA Violation

other than just bottled water – indicating that local drinking water contamination induce a secondary effect on those affected, which have negative ramifications for health.

Table 2 presents the average treatment effect over all active violation weeks. As with the bottled water sales, there is bias in the TWFE estimates, but the corresponding point estimates are not significantly different than each other. Therefore, the TWFE bias is small in this setting.

A back of the envelope calculation indicates that consumers spend an additional \$2.2 million annually on SSB as a result of nitrate violations. A large literature studies the effects of SSB consumption and the impacts of obesity (Bleich and Vercammen, 2018). An indirect effect of drinking water contamination may lead to alternative health impacts, like increased obesity rates, if consumers opt to substitute water consumption with SSBs.

	log(SSB Sales)			
	TWFE	TWFE	DiD2s	DiD2s
Nitrate Vio x w_i	0.142*	0.094*	0.179***	0.113**
	(0.055)	(0.037)	(0.040)	(0.039)
log(price)	−0.879***	−0.889***	0.012	−0.002
	(0.103)	(0.103)	(0.041)	(0.039)
Max Temp		0.008***		0.001
		(0.002)		(0.001)
Min Temp		0.002		−0.001
		(0.002)		(0.002)
Precipitation		0.000		0.000
		(0.000)		(0.000)
Num.Obs.	621 618	621 618	516 315	516 315
Std.Errors	Store & Vio	Store & Vio	Store & Vio	Store & Vio
FE: State by Year	X	X	X	X
FE: Store by Event	X	X	X	X
FE: Week by Year	X	X	X	X

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table 2: Averting Behavior Through Sugar Sweetened Bevarages

Heterogeneity

A key contribution of this paper studies the mechanisms through which demographics and resource constraints limit observed averting behavior. To estimate these effects, I estimate equation 8. For ease of interpretation, I convert all continuous demographic variables into discrete indicators, where $Z_i = 1$ if census-tract $i's$ proportion of the population for measure Z above the sample median.

Table 3 presents results from selected measure of heterogeneity. Most notably, column 3 shows significant 31.4% lower averting behavior in low access, food deserts relative to non-food deserts. Additionally, the average treatment effect in non-food deserts is almost twice that reported in table 1. This suggests that the implicitly higher price residents in rural food deserts have to pay in order to access safe, alternative drinking water in the weeks after a

	log(Bottled Water)					
	1	2	3	4	5	6
Nitrate Vio*w_i	0.173***	0.463***	0.249***	0.407***	0.180***	0.161***
	(0.032)	(0.128)	(0.042)	(0.078)	(0.027)	(0.026)
x Low Access		−0.314*				
		(0.122)				
x Low Income			−0.264**			
			(0.089)			
x > Price				−0.344**		
				(0.113)		
x > SNAP					−0.075	
					(0.149)	
x > Low Vehicle Access						0.059
						(0.099)
Num.Obs.	614 478	614 478	614 478	614 478	614 478	614 478
Std.Errors	Store & Vio.	Store & Vio.	Store & Vio.	Store & Vio.	Store & Vio.	Store & Vio.
FE: State by Year	X	X	X	X	X	X
FE: Store by Event	X	X	X	X	X	X
FE: Week by Year	X	X	X	X	X	X

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table 3: Heterogeneity in Averting Behavior: Bottled Water Sales

SDWA violation.

Additionally, other resource constraints are associated with lower averting response, including income and a more expensive retail price for bottled water. These results indicate that populations remain disproportionately exposed to the health impacts of nitrate contaminated drinking water. Regulation that assumes individuals have the same portfolio of averting responses available may exacerbate environmental inequality since low-resource communities are unable to protect themselves in the same manner as areas with higher-resource availability.

Second, table 4 displays the results for SSB sales. Similarly, food desert census-tracts display negative, but insignificant, averting response relative to non-food deserts. While none of the heterogeneity coefficients are statistically significant, they the same direction and similar relative magnitude to those of bottled water. These patterns are consistent across both bottled water and SSB purchases – suggesting that the resource constraints

	1	2	3	4	5	6
Nitrate Vio*w_i	0.113**	0.275**	0.123**	0.303***	0.117**	0.101*
	(0.039)	(0.105)	(0.039)	(0.080)	(0.042)	(0.045)
x Low Access		−0.175				
		(0.124)				
x Low Income			−0.033			
			(0.048)			
x > Price				−0.267		
				(0.153)		
x > SNAP					−0.038	
					(0.085)	
x > Low Vehicle Access						0.063
						(0.065)
Num.Obs.	516 315	516 315	516 315	516 315	516 315	516 315
Std.Errors	Store & Vio.	Store & Vio.	Store & Vio.	Store & Vio.	Store & Vio.	Store & Vio.
FE: State by Year	X	X	X	X	X	X
FE: Store by Event	X	X	X	X	X	X
FE: Week by Year	X	X	X	X	X	X

* p < 0.05, ** p < 0.01, *** p < 0.001

Table 4: Heterogeneity in Averting Behavior: Sugar Sweetened Beverage Sales

limit the purchasing ability for all products, rather than capturing a systematic correlation between consumer preferences between SSB and bottled water.[14]

7 Discussion

Nitrate contaminated drinking water pose serious health threats to infants, and possibly others. The impacts of this pollution depends on individuals' abilities to adapt to the potential health threat. However, communities affected by nitrate contaminated drinking water also often exists in resource constrained areas. These resource constraints may prevent individuals from protecting against the environmental hazard and exposed to the negative health consequences.

In this paper, I show that consumers respond, on average, by purchasing 17.3% more

[14]One long-standing claim is that consumers use SNAP funds to purchase more SSBs compared to the non-SNAP population. This claim is not supported in these findings, at least in the context of averting response, comparing estimates from comparing column 5 in tables 3 and 4.

bottled water and 11.3% more sugar sweetened beverages as a response to nitrate violations. These are relatively cheap forms of protection, which translates to roughly $4.7 million in annual averting expenditures. This amount is likely far less the counterfactual health damages if all individuals remained exposed to heightened levels of nitrates. However, individuals in food deserts exhibit a significantly dampened response, suggesting they remain vulnerable to the health damages. The final stages of this paper will study the infant-health impacts of persistent nitrate exposure.

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	log(Bottled Water Price)			
	1	2	3	4
(Intercept)	0.525***	0.092***	0.677***	0.648***
	(0.002)	(0.001)	(0.002)	(0.001)
Food Deserts	0.092***			
	(0.002)			
Convenience		1.081***		
		(0.001)		
Dollar		0.180***		
		(0.001)		
Drug		0.262***		
		(0.001)		
Mass Merchandiser		0.254***		
		(0.002)		
Urban			−0.081***	
			(0.002)	
Low Income				−0.111***
				(0.001)
Num.Obs.	747 449	747 449	747 449	747 449

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

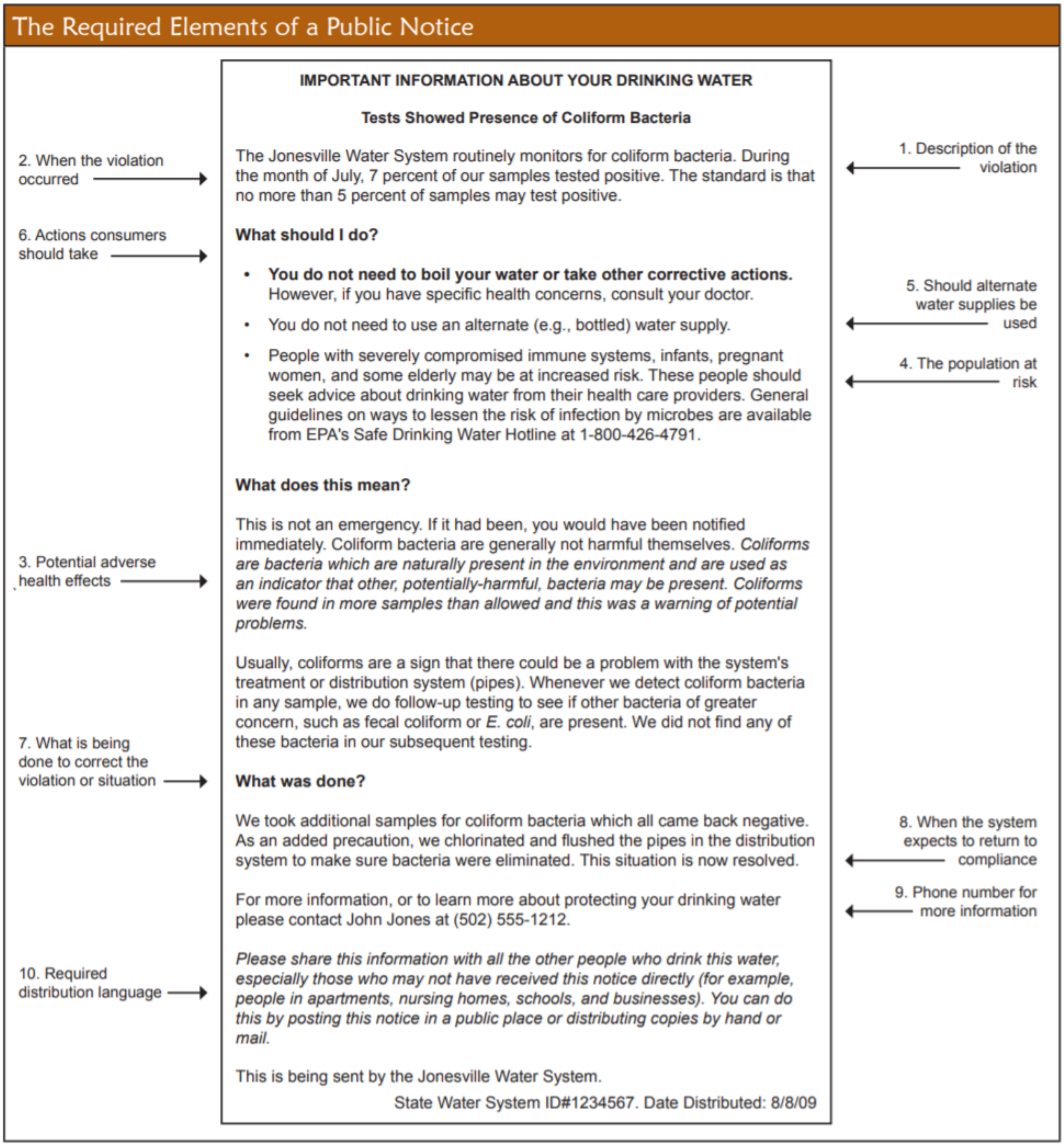
Table 5: Price of Bottled Water by Store and Location Characteristics

A Additional Tables and Figures

	log(SSB Price)			
	1	2	3	4
(Intercept)	1.248***	1.016***	1.345***	1.337***
	(0.001)	(0.001)	(0.001)	(0.000)
Food Deserts	0.054***			
	(0.001)			
Convenience		0.542***		
		(0.001)		
Dollar		0.042***		
		(0.001)		
Drug		0.237***		
		(0.001)		
Mass Merchandiser		0.088***		
		(0.001)		
Urban			−0.056***	
			(0.001)	
Low Income				−0.105***
				(0.001)
Num.Obs.	644 361	644 361	644 361	644 361

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table 6: Price of Bottled Water by Store and Location Characteristics



The Required Elements of a Public Notice

IMPORTANT INFORMATION ABOUT YOUR DRINKING WATER

Tests Showed Presence of Coliform Bacteria

The Jonesville Water System routinely monitors for coliform bacteria. During the month of July, 7 percent of our samples tested positive. The standard is that no more than 5 percent of samples may test positive.

What should I do?

- **You do not need to boil your water or take other corrective actions.** However, if you have specific health concerns, consult your doctor.
- You do not need to use an alternate (e.g., bottled) water supply.
- People with severely compromised immune systems, infants, pregnant women, and some elderly may be at increased risk. These people should seek advice about drinking water from their health care providers. General guidelines on ways to lessen the risk of infection by microbes are available from EPA's Safe Drinking Water Hotline at 1-800-426-4791.

What does this mean?

This is not an emergency. If it had been, you would have been notified immediately. Coliform bacteria are generally not harmful themselves. *Coliforms are bacteria which are naturally present in the environment and are used as an indicator that other, potentially-harmful, bacteria may be present. Coliforms were found in more samples than allowed and this was a warning of potential problems.*

Usually, coliforms are a sign that there could be a problem with the system's treatment or distribution system (pipes). Whenever we detect coliform bacteria in any sample, we do follow-up testing to see if other bacteria of greater concern, such as fecal coliform or *E. coli*, are present. We did not find any of these bacteria in our subsequent testing.

What was done?

We took additional samples for coliform bacteria which all came back negative. As an added precaution, we chlorinated and flushed the pipes in the distribution system to make sure bacteria were eliminated. This situation is now resolved.

For more information, or to learn more about protecting your drinking water please contact John Jones at (502) 555-1212.

Please share this information with all the other people who drink this water, especially those who may not have received this notice directly (for example, people in apartments, nursing homes, schools, and businesses). You can do this by posting this notice in a public place or distributing copies by hand or mail.

This is being sent by the Jonesville Water System.

State Water System ID#1234567. Date Distributed: 8/8/09

Figure 6: Public Notification Example and Reqirements

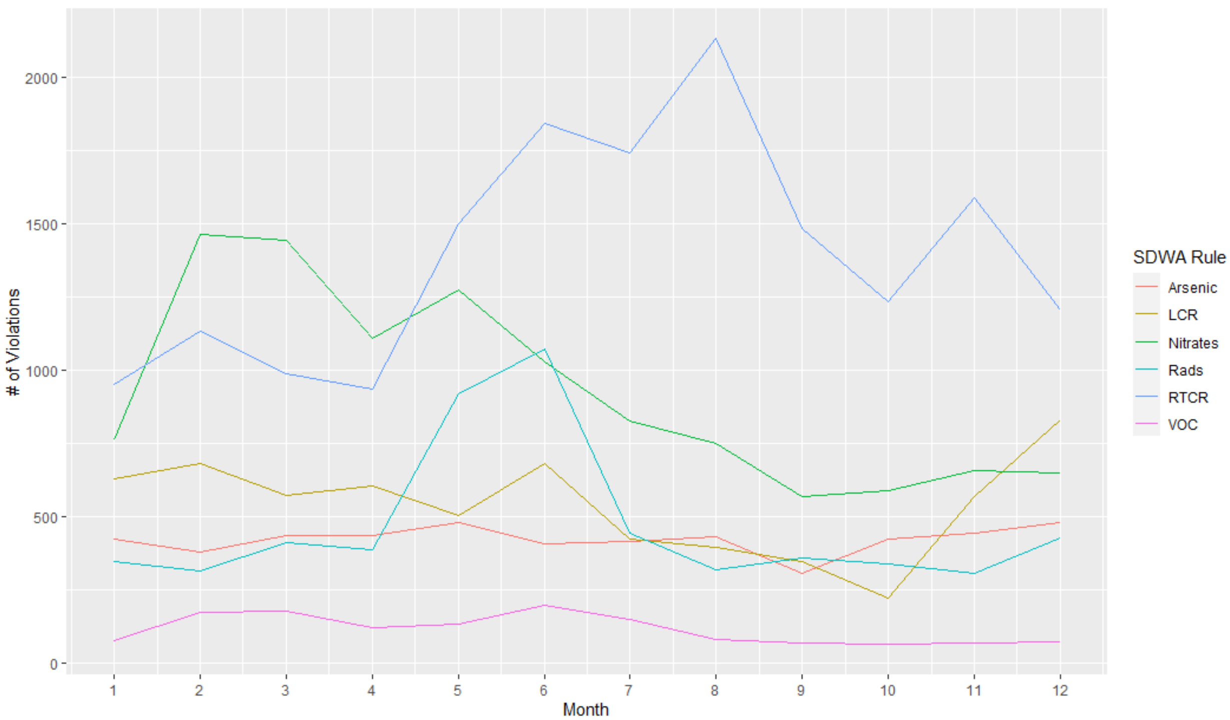


Figure 7: Sum of SDWA Violations by Type

NOTE: LCR = Lead/Copper Rule, Rads= Radionucleotides, RTCR= Revised Total Coliform Rule, VOC= Volatile Organic Compounds.

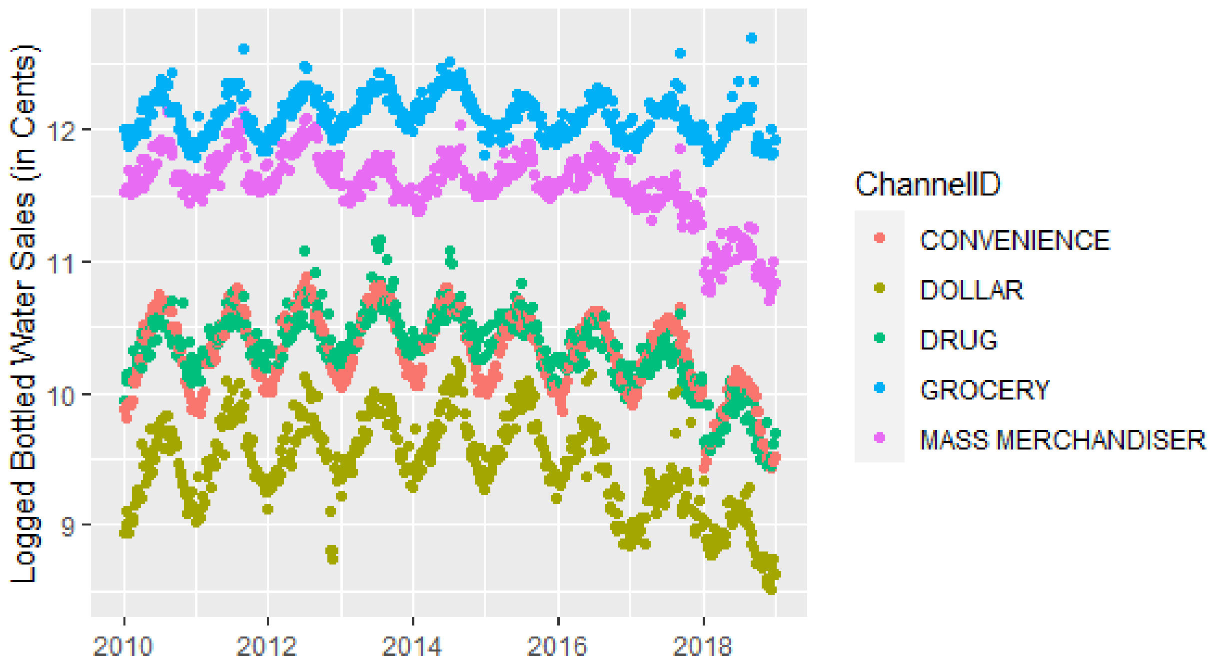


Figure 8: Raw bottled Water Sales by Store Type

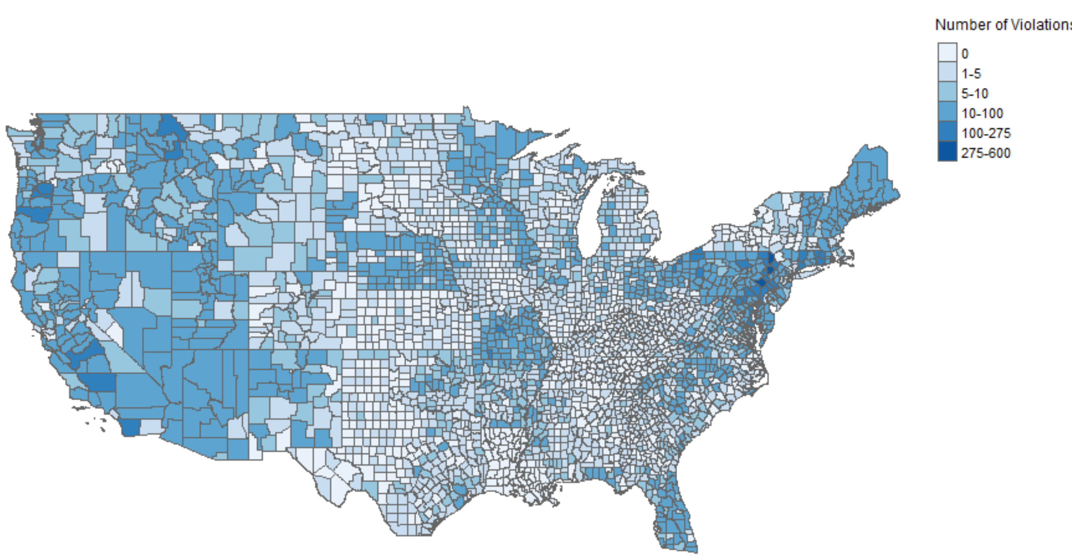


Figure 9: Caption