National trends in drinking water quality violations

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Ensuring safe water supply for communities across the United States is a growing challenge in the face of aging infrastructure, impaired source water, and strained community finances. In the aftermath of the Flint lead crisis, there is an urgent need to assess the current state of US drinking water. However, no nationwide assessment has yet been conducted on trends in drinking water quality violations across several decades. Efforts to reduce violations are of national concern given that, in 2015, nearly 21 million people relied on community water systems that violated health-based quality standards. In this paper, we evaluate spatial and temporal patterns in health-related violations of the Safe Drinking Water Act using a panel dataset of 17,900 community water systems over the period 1982–2015. We also identify vulnerability factors of communities and water systems through probit regression. Increasing time trends and violation hot spots are detected in several states, particularly in the Southwest region. Repeat violations are prevalent in locations of violation hot spots, indicating that water systems in these regions struggle with recurring issues. In terms of vulnerability factors, we find that violation incidence in rural areas is substantially higher than in urbanized areas. Meanwhile, private ownership and purchased water source are associated with compliance. These findings indicate the types of underperforming systems that might benefit from assistance in achieving consistent compliance. We discuss why certain violations might be clustered in some regions and strategies for improving national drinking water quality.

drinking water | water quality | violations | Safe Drinking Water Act | regulatory compliance

Ensuring access to safe drinking water poses a challenge for US water systems in the face of aging infrastructure, impaired source water, and strained community finances. Communities across the country have been impacted by recent cases of impaired water quality. The Flint crisis exposed as many as 98,000 residents to elevated levels of lead, disinfection byproducts (DBPs), and *Escherichia coli* and *Legionella* bacteria. In addition, substantial populations have coped with interruptions to potable water supply due to the Elk River chemical spill in West Virginia and unregulated toxins formed during algal blooms near Toledo, Ohio. These well-publicized events motivate the need to assess the current state of US drinking water quality. How widespread are violations? Are violations more prevalent in vulnerable communities, such as low-income and rural areas? Do utility characteristics, such as private ownership and origin of source water, influence the likelihood that violations occur?

Identifying threats and potential improvements to water services are needed, given that an estimated 16.4 million cases of acute gastroenteritis each year in the United States are attributed to community water systems (CWSs) (1). Equity concerns are also gaining recognition as evidence builds regarding lower-income and minority communities receiving poor quality water (2, 3). Generally, water systems in the United States provide reliable and high-quality drinking water. Violations tend to be infrequent. However, in a given year, about 7–8% of CWSs report at least one health-based violation. While this rate is relatively low, improved compliance is needed to ensure safe drinking water nationwide. The Environmental Protection Agency (EPA) has a strategic objective to achieve consistent compliance for 91% of the population served by CWSs (4). However, from 1993 to 2009, compliance with Safe Drinking Water Act (SDWA) health-based regulations ranged from 79 to 94% of the population served by CWSs (4).

Targeting utilities that are underperforming is one approach to improve compliance and consistently provide safe drinking water. Currently, state enforcement agencies lack a systematic procedure to select systems for additional monitoring and inspection. Routine quality monitoring is specified at the federal level and allows for more frequent sampling at systems with recent violations. However, no guidelines exist for identifying systems without recent reported violations that could benefit from additional oversight. Identifying hot spots and vulnerability factors associated with violations could better direct enforcement activity to struggling utilities and allow for increased compliance across the country.

This paper presents a national assessment of trends in drinking water quality violations across several decades. Currently, there is not a good understanding of quality violations and few peer-reviewed studies have been done on SDWA compliance. Past analyses of the association between water system characteristics and violations have generally been limited in terms of geographic area and/or study period. Several studies focus on a single state (e.g., refs. 3 and 5–7). The two studies in the peer review literature that address SDWA violations nationwide have study periods limited to a single year (8) or 7 y (9). Rubin (8) describes summary statistics of violations for four SDWA rules for the year 2011. A key finding is that similar proportions of small and large systems incur health-based violations. However, given that only

Significance

Drinking water contaminants pose a harm to public health. Some can cause immediate illness, such as the 16 million cases of acute gastroenteritis that occur each year at US community water systems. Here, we show that health-based drinking water quality violations are widespread, with 9–45 million people possibly affected during each of the past 34 years. While relatively few community water systems (3–10%) incur health-based violations in a given year, improved compliance is needed to ensure safe drinking water nationwide. Currently, state enforcement agencies lack a systematic procedure to select systems for additional inspection and monitoring. We identify hot spots and vulnerability factors associated with violations, which can allow public policies to target underperforming water systems.

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summary statistics are presented, results do not isolate the association between violations and specific utility characteristics. Meanwhile, Wallsten and Kosec (9) develop count regressions that relate community and water system characteristics to SDWA violations from 1997 to 2003. The study found that private ownership does not generally affect compliance.

In this study, we assess spatial and temporal trends in health-based violations as well as vulnerability factors that may influence violation occurrence. We assemble a panel dataset that includes 17,900 CWSs in the United States from 1982 to 2015. We combine demographic information from the US Census with data on SDWA violations and CWS characteristics from the EPA Safe Drinking Water Information System (SDWIS). Spatial trends and hot spots are assessed via local spatial autocorrelation. Vulnerability factors, which include CWS and demographic characteristics, are assessed using probit regressions. Our main research objectives are to (*i*) characterize the extent and severity of drinking water quality violations across the United States, and (*ii*) identify characteristics of water systems and communities associated with violations that can be used to better target enforcement activity.

Background

The SDWA, passed in 1974, authorizes the EPA to regulate drinking water quality. Standards are set at the federal level and states have primary responsibility for enforcement. When a water system fails to meet an EPA-mandated drinking water standard, a drinking water violation can be issued. Violation occurrence and reporting may differ across states due to differences in enforcement, financial resources, source water quality, and treatment costs (10). In addition, states are able to set stricter standards than federal SDWA rules.

Not all violations pose immediate health concerns. This study focuses on health-based violations, which include maximum contaminant levels (MCLs), maximum residual disinfectant levels, and treatment techniques. Standards for contaminants that can trigger health-based violations are specified by the National Primary Drinking Water Regulations. We exclude monitoring and reporting violations, which have poor data quality since only a small portion of these violations (9–23%) are reported to the national SDWIS database (11). Both naturally occurring and manmade contaminants can trigger health-based violations. These contaminants or contaminant indicators include total coliform, turbidity, DBPs, radionuclides, and organic and inorganic chemicals.

Materials and Methods

Data. We construct a balanced panel dataset that includes CWSs with consistent reporting to the EPA SDWIS over the study period, 1982–2015. To be included in the study, a public water system must be classified as a CWS, serve over 500 people, begin reporting violations in 1982 or prior, and be located within the continental United States. Violation records and CWS characteristics were obtained from the SDWIS. Community characteristics at the county level were obtained from the US Census. The unit of analysis in this study is the utility year.

Violation records from the SDWIS indicate whether or not a MCL was exceeded or a treatment technique was not met. Contaminant concentrations or sampling results for regular monitoring are not available. Another limitation of the SWDIS is underreporting of some violations. To address underreporting, we emphasize the regression results for total coliform violations, which are more accurately reported than other types of violations (12). Also, we exclude very small systems serving fewer than 500 people since these are more likely to have inadequate reporting practices (8). Overall, these violations data represent the best national information that is currently available for drinking water quality.

Water system characteristics include type of source water, service population, and ownership type. County-level locations of each CWS are defined based on the CWS address provided in the SDWIS. Community characteristics are county-level variables from the US Census and represent annual values for the 1982–2015 study period. Characteristics include household income, housing density, and percent nonwhite population. Since CWSs are not required to collect demographic information about customers, census information can provide some insight into possible association between water quality violations and community characteristics. Data availability was sufficient to interpolate values for intercensus years. A more detailed description of the data is provided in *SI Data*.

Hot-Spot Analysis of Violations. We use spatial autocorrelation to describe and map spatial clusters of SDWA violations. The local $G_i^*(d)$ statistic (local Getis–Ord statistic) is used to test the statistical significance of local clusters (13). For each county, we estimate a local Getis–Ord statistic as a function of distance between neighboring counties and violation occurrence. Further description is provided in *SI Materials and Methods*.

Vulnerability Factors Associated with Violations. Probit regression is used to assess the relationship between drinking water quality violations and characteristics of water systems and communities. The likelihood of a water supplier incurring a health-based quality violation is modeled as follows:

$$\Pr(y_{it}=1|X)=\Phi\left(\beta_0+\beta_x x_i+\gamma_{jt}C_{jt}+\alpha_t T_t+\phi_k S_k\right), \qquad [1]$$

where y_{it} is a binary indicator of violation occurrence for water supplier i in year t. The probability of a CWS having a violation is estimated as a function of time-invariant water supplier characteristics (x_i) and county-level community characteristics (C_{jt}) for county j in year t. Each water supplier i is associated with a county j and state k. The model includes dummy variables for each year (T_t) and state (S_k). Year dummy variables control for changes in federal regulations or compliance over time. Meanwhile, controlling for state-level effects is important because the SDWA is enforced primarily at the state level. State-level enforcement can differ due to variation in sampling protocols, technical capacity, and financial resources. The coefficient for the state dummy will then indicate the average propensity for water quality violations being reported in a state due to either water quality violations or enforcement effort. Covariates included in the probit model were selected based on a careful review of the literature, lasso regression, and specification tests.

Models are specified for total violations and for total coliform violations. The total coliform models may provide more accurate estimates of associations between violations and covariates since (*i*) total coliform is regulated in a consistent manner throughout the study period and (*ii*) Total Coliform Rule (TCR) violations are reported more accurately than other types of MCL violations (12). We estimate coefficient values and average marginal effects. Average marginal effects are useful for interpretation; they provide a single estimate of the effect of each covariate on $\Pr(Y=1)$. For more detail on our regression analysis and calculation of average marginal effects, see *SI Materials and Methods*.

Results

Summary Statistics. We find that water quality concerns extend well beyond Flint. In 2015, 9% of CWSs in our study sample violated health-based water quality standards, affecting nearly 21 million people. During each of the past 34 y, 9–45 million people were affected, representing 4–28% of US population.

Our balanced panel dataset contains 34 y and 17,900 CWSs, which serve 87% of the population supplied by CWSs in the continental United States. Full summary statistics and variable definitions are provided in Table S1. About 8.0% of the 608,600 utility-year observations had some type of health-based violation, while 4.6% had a total coliform violation. In total, there were 95,754 health-based violations and total coliform was the most prevalent type of violation, representing about 37% of all violations (Fig. 1). Fecal coliform violations are relatively rare; only 2,138 occurred during our study period. Violations categorized as "other" contaminants were also prevalent, representing about 36% of violations. DBPs comprised the majority of other violations. Violations of treatment rules and nitrate are much less common (21% of total). Descriptions of violation categories are provided in Table 1 and *SI Data*.

Differences in the rate of violation occurrence exist across characteristics of CWSs and communities (Table S2), as discussed in *SI Results*.

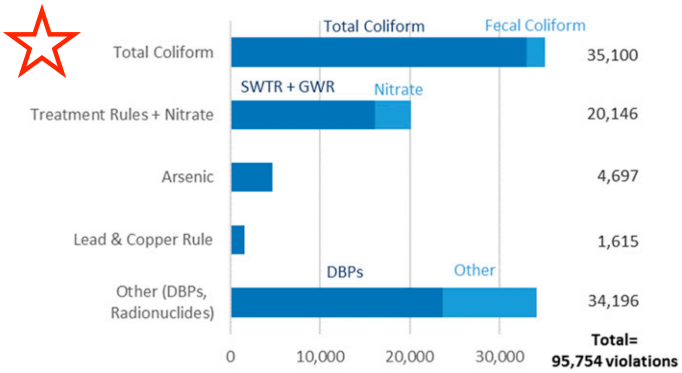

Fig. 1. Number of health-based violations, 1982–2015, by contaminant type.

Time Trends. We find that significant time trends exist for some states. State trends are estimated as deviations from the national time trend (Table S5). Twenty states deviate above the national trend, including Nebraska, Arkansas, North Carolina, and Southwest states—New Mexico, Texas, and Oklahoma (Fig. S4). Only three states are below the national time trend—Washington, Iowa, and Illinois (Fig. S4*A*). Similar results are found for time trends of total coliform violations, except more states have a declining trend (Fig. S4*B*). At the national level, the linear time trend of violations is insignificant once we control for the year dummy variables (Table S5).

Violation occurrence has fluctuated over the history of the SDWA. Fluctuations in number of violations can be attributed to a variety of factors, including regulatory changes, enforcement capacity, raw water quality, and treatment capabilities. Fig. 2 depicts the number of health-based violations across the CWSs included in the analysis. Total violations more than double over the 34-y study period. This increase is partially driven by new regulations. The number of regulated contaminants has dramatically increased from 22 (in 1974) to 91 (at present). Table 1 provides a list of EPA rules and enforcement dates.

Spikes in violations appear to occur immediately after new federal regulations. Utilities might undergo a learning and adjustment process when coping with new regulations. For example, violation counts of DBPs and other chemicals dramatically rose after 2002, when the Stage 1 DBPs Rule became enforceable. The time dummy variables in our regression analysis capture federal rule changes, as evidenced by positive and significant coefficient values after major regulation changes (Fig. S3).

Substantial differences across time also exist between rural and urban areas, in terms of number of violations per CWS (Fig. 3). Furthermore, low-income rural areas have a larger compliance gap than higher-income rural areas. DBP violations account for much of this gap. Differences between rural and suburban areas became pronounced and statistically significant after new DBP rules in the early 2000s.

Spatial Trends. Violations also vary considerably across geographic locations. Fig. 4A shows a map of the total number of violations (1982–2015) per CWS in a given county. Some of the counties with the highest prevalence of violations are rural, located in Texas, Oklahoma, and Idaho. Total coliform violations (Fig. 4B) are especially prevalent in the West and Midwest. A variety of factors could contribute to differences across counties, including the quality of source water and state-level enforcement.

Fig. 4 depicts high violation prevalence throughout Oklahoma and parts of Idaho. In some areas, total coliform comprises a large portion of total violations. This is especially true in Nebraska (56% of all violations during the study period are total coliform), Missouri (42%), New Hampshire (35%), and Massachusetts (81%). There are several locations that have high prevalence of total violations, but not total coliform, such as Texas and Kansas. The proportion of total coliform violations has implications for interpreting regression results from models specified for total coliform and total violations.

Spatial differences in violation incidence vary considerably across time. This is particularly true for the Southwest region (includes Arizona, Oklahoma, New Mexico, and Texas), which had similar violation incidence as other regions until the early 2000s. After the Stage 1 DBP rule in the early 2000s, violation incidence dramatically increased and is more than triple that of other regions (Fig. S1). DBPs account for the vast majority of violations in the Southwest. This region might be particularly susceptible to DBP violations due to high summer temperatures (14) and high levels of total organic carbon in source water. Furthermore, Oklahoma requires a high level of minimum disinfectant residual (1.0 mg/L total chlorine). This could cause

Table 1. Description of categories of drinking water quality violations

Study category	Contaminants	SDWA rules
Total coliform	Fecal coliform (*E. coli*)	NIPDWR, TCR, RTCR
	Total coliform	
Treatment rules plus nitrate	Nitrate	NIPDWR
	Nitrite	Phase II
	Turbidity	NIPDWR, SWTR, IESW, LT1ESW
	Cryptosporidium	IESW, LT1ESW, LT2ESW
	Giardia lamblia	SWTR, GWR
	Viruses	SWTR, GWR
Arsenic	Arsenic	NIPDWR, Arsenic
Lead plus copper	Lead, copper	NIPDWR, LCR, RLCR
Other	DBPs	Trihalomethanes, Stage 1 DBPs, Stage 2 DBPs
	Radionuclides	NIPDWR, Radionuclides
	Inorganic and organic chemicals	NIPDWR, Phase I, Phase II, Phase V

Notes: SDWA rule names and enforcement dates are as follows: Arsenic, Arsenic Rule (2006); GWR, Ground Water Rule (2009); IESW, Interim Enhanced Surface Water Treatment Rule (2002); LCR, Lead and Copper Rule (1992); LT1ESW, Long Term 1 Enhanced Surface Water Treatment Rule (2005); NIPDWR, National Interim Primary Drinking Water Regulations (1977); Phase I Rule (1989); Phase II Rule (1992); Phase V Rule (1994); Radionuclides, Radionuclides Rule (2003); RLCR, Revised Lead and Copper Rule (2007); RTCR, Revised Total Coliform Rule (2016); Stage 1 DBPs, Stage 1 Disinfectants and Disinfection By-products Rule (2002–2004); Stage 2 DBPs, Stage 2 Disinfectants and Disinfection By-products Rule (2012–2013); SWTR, Surface Water Treatment Rule (1993); TCR, Total Coliform Rule (1990); and Trihalomethanes, Total Trihalomethanes (1981–1983).

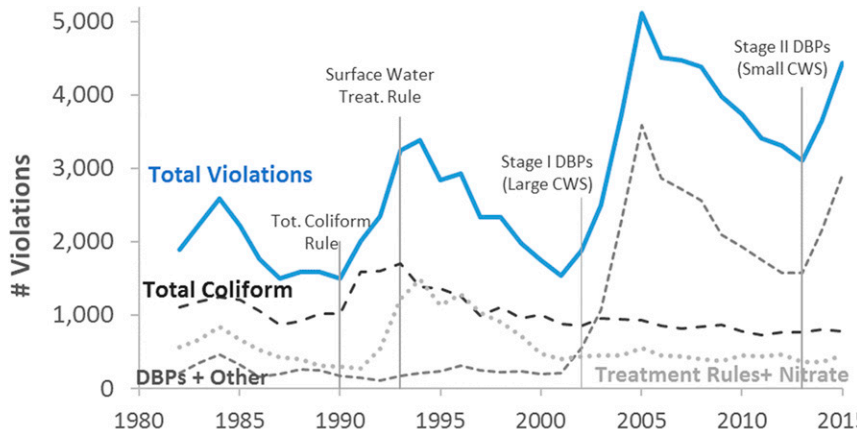

Fig. 2. Number of health-based violations, 1982–2015. Gray bars represent dates that major components of rules became enforceable.

DBP issues during high temperatures, when effective chlorine levels decline and additional disinfectant might be needed.

Violation Hot Spots. Intense hot spots of SDWA violations are identified in Oklahoma and parts of Texas, based on local spatial autocorrelation (Fig. 5). While these findings are somewhat similar to Fig. 4A, the hot-spot analysis offers the advantage of determining whether clusters of violations are significant. Similar spatial clusters are found for violation counts per CWS and for binary indicators of violation occurrence. Hot-spot locations tend to include water systems with repeat violations. In our overall sample, only 11% of the CWSs have repeat violations, which involve two or more subsequent years of a violation. The states with the greatest proportion of CWSs with repeat violations are Oklahoma (43% of CWSs in the state), Nebraska (35%), and Idaho (33%).

When assessing hot spots over time, we find that spatial clusters of violations have shifted during the 34-y study period (Fig. S2). In the earliest decade of the study period (1982–1992), significant hot spots of violation counts are present in the Northwest, southern California, and Pennsylvania. Meanwhile, in the following decade (1993–2003), the magnitude and significance of the estimated z-scores increases in Oklahoma, Tennessee, and Idaho. Finally, in more recent years (2004–2015), significant hot spots appear in Texas and increase in parts of Oklahoma.

Regression Results. Regression results are presented both as coefficient estimates (Table S3) and average marginal effects (Table S4). Our major findings are that violation occurrence is significantly associated with less urbanized areas and lag violations, while compliance is associated with purchased water source and private ownership.

Violations in the prior year are significantly associated with current year violations. This provides further evidence that recurring violations at a given water system are a concern. Repeat violations are prevalent in locations of spatial clustering of violations, as previously discussed in the section on violation hot spots.

Water systems that purchase treated water from other utilities show a lower propensity for violations. Wholesale water providers may have greater capacity to achieve regulatory compliance (9). The probability of a total coliform violation for a utility purchasing water is 0.9% lower than a utility with a groundwater source (Table S4). Similar results are found for total violations, although the estimated marginal effects are smaller in magnitude.

Privately owned utilities appear to be less vulnerable to violations than public ownership, which agrees with previous findings (5, 9, 15). The probability of a total coliform violation for a privately owned utility is 0.5% lower than a government-owned utility. A larger association was found for total violations (1.0%). This result might be attributable to private firms facing the possibility of takeover by a municipal government, which could lead to greater compliance (15). Large private utilities in particular have considerable resources at stake should they deliver poor-quality water and face lawsuits or takeover. Our coefficient estimates suggest that the interaction term between private and large firms is significantly associated with fewer violations (Table S3).

Less urbanized areas are associated with greater likelihood of violation occurrence (Table S6). Meanwhile, our indicator of minority, low-income populations is associated with higher likelihood of total coliform violations. These findings might indicate environmental justice concerns for rural areas and minority communities. Further research is warranted to understand environmental justice issues and which communities are particularly at risk.

Utilities in more rural, less urbanized areas tend to have less capacity to comply with quality regulations and face financial strain due to declining populations and lower incomes (16). Furthermore, small, rural CWSs might especially struggle, given that we estimate the highest predicted probability of violation occurs at small, rural CWSs relying on surface water sources (Fig. S5). Last, we find larger negative associations for total

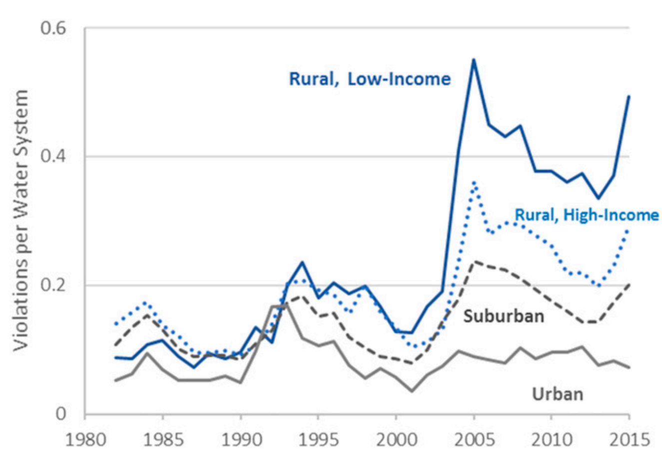

Fig. 3. Total violations per water system, by housing density category and income group. Low-income counties have median household income below 75% of national median household income. In year 2015, national median household income was $55,775 and 45% of rural CWSs are located in counties defined as low-income.

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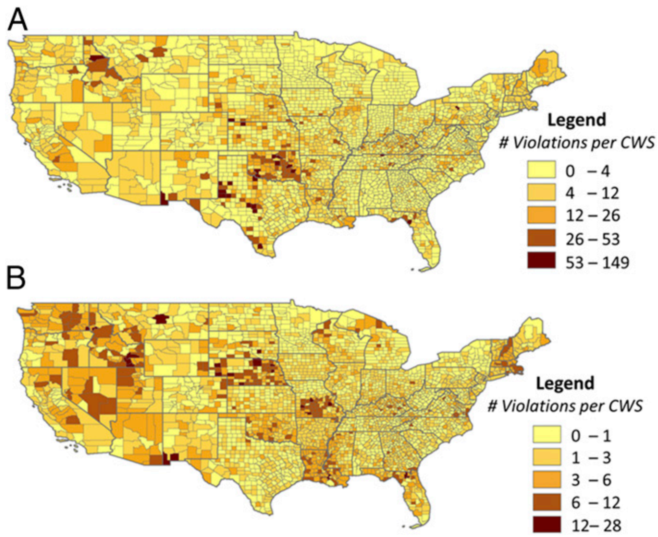

Fig. 4. Number of violations per CWS, 1982–2015, by county. (*A*) Total violations. (*B*) Total coliform violations. Intervals in legend are selected based on the Jenks natural breaks classification method.

violations, compared with total coliform. This might be partly attributable to rural systems facing challenges in complying with DBP rules. Lower housing density and water flows through distribution networks can lead to older "water age," which enables DBP formation (17). Rural systems may also have less technical capacity and financial resources to implement infrastructure upgrades or frequent flushing of the system.

In our analysis, urbanization is the combination of housing density, median household income, and percent nonwhite population. It is not informative to interpret the individual coefficient estimates of these three variables since they are moderately correlated. The correlation matrix of coefficient estimates for model 2 indicates correlations between housing density and median income ($r = -0.54$) as well as housing density and nonwhite population ($r = -0.37$). Therefore, we conduct principal-component regression to address these correlations, as described in *SI Results*. In this way, the association between violations and these three correlated variables can be better understood since the variables are transformed intro uncorrelated components. We interpret the first principal component (PC) as an indicator of urbanization; it represents the average effect of all three variables. Meanwhile, the second PC represents the contrasting effect, and we interpret it to be an indicator of minority, low-income populations.

In all models, the P value of the likelihood ratio χ^2 is less than 0.01, which indicates that each model as a whole is statistically significant. For all model specifications, bootstrapped estimates produce similar results. Our preferred specifications are the total coliform models with interaction terms (models 4 and 6), since total coliform violations have more accurate reporting and are regulated more consistently than other violations during the study period.

Discussion

Targeting utilities that are underperforming is one approach to improve compliance and consistently provide safe drinking water. Identifying hot spots and vulnerability factors associated with violations could better direct enforcement activity and inform the allocation of federal grant funds that assist state-level enforcement.

Intense hot spots of SDWA violations and increasing time trends are detected in some states, especially Southwest states such as Oklahoma and Texas. Notably, repeat violations are prevalent in locations of intense spatial clustering of violations. Water systems in these locations are prone to recurring issues, as evidenced by our regression analysis that found violations in the prior year are significantly associated with current year violations. Repeat violations have been a focus of EPA regulation in recent years.

Beyond temporal and spatial trends, we also find major vulnerability factors. Violation occurrence is found to be associated with rural areas, while compliance is associated with purchased water source and private ownership. These findings indicate the types of communities that might benefit from greater regulatory oversight and assistance in achieving consistent compliance with water quality standards.

Regulatory compliance can be a challenge for rural systems due to limited financial resources and technical expertise. A smaller customer base can mean less revenue for infrastructure improvements, repayment of debt, and salaries to attract technically skilled operators. Small systems also face restricted access to loans and outside financing, compared with larger systems with higher credit ratings (18). This presents a challenge for complying with stricter standards, especially those that require capital modifications or new operational procedures. A new rule for DBPs in the early 2000s led to a dramatic increase in violations in rural areas. The compliance gap was especially large between low-income rural areas and more urban counties. We also find that low-income, minority communities may face higher likelihood of certain violations, such as total coliform.

Meanwhile, water systems that rely on purchased water show a lower propensity for violations. Purchased water is produced by wholesale water providers, which may have greater capacity to achieve regulatory compliance (9). In addition, privately owned utilities are found to be less vulnerable to violations than government ownership. In particular, large private firms are associated with lower likelihood of violation. This might be attributable to large private firms having considerable resources at stake should they deliver poor-quality water and face lawsuits or takeover by a municipal government.

Several policy implications emerge from our findings. First, prioritization of technical guidance and financial assistance could benefit underperforming systems. Expansion of training and assistance could address a variety of operational issues, including source water protection and development of procedures for monitoring and maintenance, which are the most common system deficiencies (19). Second, merging and consolidation of systems, where feasible, could provide a way to achieve economies of scale for adequate treatment technologies. Feasibility of consolidation will be influenced by existing infrastructure, distance, and liability concerns. The electricity sector has undergone substantial restructuring since the mid-1990s, through consolidation and separation of generation and delivery. Third, purchased water contracts might provide a cost-effective way for utilities to comply with regulations, especially small water systems.

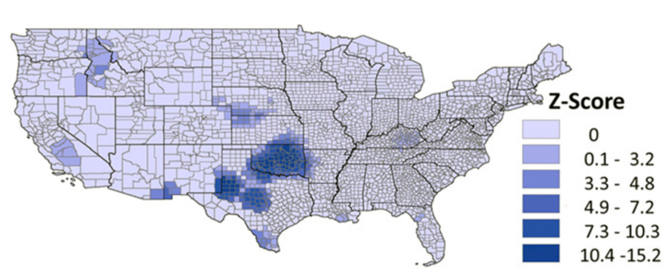

Fig. 5. Spatial clusters (hot spots) of health-based violations, 1982–2015. Hot spots for number of total violations per CWS, by county. Intervals in legend are selected based on the Jenks natural breaks classification method.

These findings are relevant for larger questions regarding national-level water quality regulations: (*i*) How can regulatory rules consider linkages between the SDWA and the Clean Water Act?, (*ii*) Should drinking water standards be set at a subnational level?, and (*iii*) What strategies can improve data collection and monitoring of violations?

Regulation and enforcement activities that better consider the linkages between the SDWA and the Clean Water Act could address concerns over impaired source water. Vulnerable communities may face the additional challenge of rising compliance cost that is driven by source water impairment. Further research is needed regarding the extent to which treatment costs at public water systems might be affected by emerging contaminants and potential changes to Clean Water Act standards or enforcement. Considering the interactions of state and federal regulations is also crucial. For example, the combined effects of state-level residual disinfectant requirements, poor quality source water, and high summer temperatures might cause the Southwest region to be particularly susceptible to DBP violations.

National SDWA rules ensure that all water systems share the same minimum water quality standards. However, variation in standards across states or municipalities might increase efficiency since this would reflect local preferences for trade-offs between risk reduction and intervention cost (20). Subnational standards might allow net benefits to be realized in specific locations, since net benefits will vary based on compliance cost, contaminant prevalence, vulnerable populations, and other factors. In addition, subnational rules might allow a broader range of contaminants to be regulated, especially those that only affect specific localities. At present, the SDWA only regulates contaminants that frequently occur at harmful levels across the country. An important area for future research is assessing the welfare implicates of uniform, national-level standards compared with subnational standards.

Last, there is a nationwide need for improved data collection and monitoring of violations. Underreporting of SDWA violations deserves attention, given that an estimated 26–38% of health-based violations are either not reported or inaccurately reported to the national SDWIS database. Capturing a more complete record of violations is crucial for addressing potential public health concerns. A major barrier to improved reporting is substantial reductions in state and federal funding for enforcement activities. State funding declined a third from 2001 to 2011, while workloads have increased due to newly promulgated rules (21).

Beyond restored funding, technology developments could enable improved monitoring and data management. In-pipe sensors may offer a game-changing way to continuously monitor water quality within a distribution system. However, sensors are in the early stages of development and their use is rare in practice due to low accuracy and high costs of capital and operation. A more immediate development is improved data management. A new cloud-based reporting system, SDWIS Prime, might allow greater consistency in reporting across states. Currently, each state maintains its own database, which can lead to inaccuracies during data transfer from utilities to the state to the federal SDWIS. This new system also automates compliance determination, which can reduce labor expense. In combination with cloud-based reporting, algorithms should be developed that can automatically check for outliers. This will facilitate analytics on large volumes of data and allow emerging problems to be identified at an individual utility or across a region.

Overall, this study informs a more directed approach to increase compliance with drinking water quality regulations. While quality violations are generally infrequent, some do reflect a risk to human health. Identifying hot spots and vulnerability factors associated with violations can allow public policies to target underperforming water systems. Reducing water quality violations can lead to improved health outcomes and less disparity in water service.

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1. Messner M, et al. (2006) An approach for developing a national estimate of waterborne disease due to drinking water and a national estimate model application. *J Water Health* 4:201–240.
2. Stillo F, MacDonald Gibson J (2017) Exposure to contaminated drinking water and health disparities in North Carolina. *Am J Public Health* 107:180–185.
3. Balazs C, Morello-Frosch R, Hubbard A, Ray I (2011) Social disparities in nitrate-contaminated drinking water in California's San Joaquin Valley. *Environ Health Perspect* 119:1272–1278, and erratum (2011) 119:A509.
4. US Environmental Protection Agency (2009) Factoids: Drinking water and ground water statistics for 2009 (US Environmental Protection Agency, Washington, DC), EPA-816-K-09-004.
5. Rahman T, Kohli M, Megdal S, Aradhyula S, Moxley J (2010) Determinants of environmental noncompliance by public water systems. *Contemp Econ Policy* 28:264–274.
6. Guerrero-Preston R, Norat J, Rodríguez M, Santiago L, Suárez E (2008) Determinants of compliance with drinking water standards in rural Puerto Rico between 1996 and 2000: A multilevel approach. *P R Health Sci J* 27:229–235.
7. Pike W (2004) Modeling drinking water quality violations with Bayesian networks. *J Am Water Res Assoc* 40:1563–1578.
8. Rubin S (2013) Evaluating violations of drinking water regulations. *J Am Water Resour Assoc* 105:E137–E147.
9. Wallsten S, Kosec K (2008) The effects of ownership and benchmark competition: An empirical analysis of U.S. water systems. *Int J Ind Organ* 26:186–205.
10. Noll R (2002) The economics of urban water systems. *Thirsting for Efficiency: The Economics and Politics of Urban Water System Reform*, ed Shirley M (Pergamon, Amsterdam), pp 43–63.
11. US Environmental Protection Agency (2004) EPA claims to meet drinking water goals despite persistent data quality shortcomings (US Environmental Protection Agency, Washington, DC), Report No. 2004-P-0008.
12. US Environmental Protection Agency (2002) Data reliability analysis of the EPA safe drinking water information system/federal version (SDWIS/FED) (US Environmental Protection Agency, Washington, DC), EPA 816-R-00-020.
13. Getis A, Ord J (1992) The analysis of spatial association by use of distance statistics. *Geogr Anal* 24:189–206.
14. Rodriguez MJ, Sérodes JB (2001) Spatial and temporal evolution of trihalomethanes in three water distribution systems. *Water Res* 35:1572–1586.
15. Konisky D, Teodoro M (2016) When governments regulate governments. *Am J Pol Sci* 60:559–574.
16. National Research Council (1997) Ensuring small water supply system sustainability. *Safe Water from Every Tap: Improving Water Service to Small Communities* (National Academy Press, Washington, DC), p 153.
17. Al-Jasser AO (2007) Chlorine decay in drinking-water transmission and distribution systems: Pipe service age effect. *Water Res* 41:387–396.
18. US Environmental Protection Agency (2001) *1999 Drinking Water Infrastructure Needs Survey Modeling the Cost of Infrastructure* (US Environmental Protection Agency, Washington, DC).
19. Oxenford J, Barrett J (2016) Understanding small water system violations and deficiencies. *J Am Water Works Assoc* 108:31–37.
20. Dinan T, Cropper M, Portney P (1999) Environmental federalism: Welfare losses from uniform national drinking water standards. *Environmental and Public Economics*, eds Panagariya A, Portney P, Schwab R (Edward Elgar, Cheltenham, UK), pp 13–31.
21. Association of State Drinking Water Administrators (2013) An analysis of state drinking water programs' resources and needs (Association of State Drinking Water Administrators, Arlington, VA).