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Trends in microbiological drinking water quality violations across the United States

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This study analyzed temporal trends in health-based drinking water quality violations, and both temporal and geographic trends in microbiological drinking water quality violations for U.S. public water systems. We especially focused on microbiological regulations that apply to all public water systems, *i.e.*, the total coliform rule (TCR), which became effective in 1990, and its successor, the revised total coliform rule (RTCR), which was implemented in 2016. By using the U.S. Environmental Protection Agency (EPA)'s Safe Drinking Water Information System, we determined that changes in regulations greatly impacted temporal trends in health-based violations. TCR health-based violations were the most common type of health-based violation, partly because the TCR required more monitoring than any other regulation and was one of the few rules that applied to transient non-community water systems, which make up a large fraction of all public water systems and often have limited resources. As expected by the U.S. EPA, the implementation of the RTCR caused an immediate decrease in the number of health-based violations due to specific changes in what constitutes a health-based violation under the RTCR *versus* the TCR. The number and severity of health-based coliform violations varied with system size and type, and this imbalance was exacerbated under the RTCR. Notably, while very small public water systems and transient non-community water systems already had more violations per system than their counterparts, this disparity was amplified upon adoption of the RTCR. Geographic analyses showed that the Great Lakes region had high numbers of total health-based coliform violations. While fewer data exist to analyze violations normalized by the number of systems, an initial exploration of health-based coliform violations per system resulted in different geographic patterns. We conclude with a discussion of the potential benefits of future predictive modeling to identify public water systems that would benefit from technical and financial assistance to improve their water quality.

Water impact

Microbiological drinking water quality violations are the most common violation of the U.S. EPA Safe Drinking Water Act and these violations were disproportionately attributed to very small systems and transient non-community water systems. Future predictive modeling could be used to identify public water systems that would benefit from technical and financial assistance to improve their water quality.

1. Introduction

Most people in the United States (U.S.) and other high income countries typically do not worry about the microbiological quality of drinking water, except when confronted with media coverage of high profile outbreaks (*e.g.*, cryptosporidiosis outbreak in Milwaukee, Wisconsin in 1993;[1] Legionnaires' disease outbreak in Flint, Michigan in 2014–2015 (ref. 2)). Nevertheless, drinking water-associated infections and outbreaks are relatively common; the most recent surveillance report for drinking water-associated disease and outbreaks in the U.S. indicated that, during 2013–2014, 42 outbreaks were reported to the Centers for Disease Control and Prevention, resulting in at least 1006 cases of illness, 124 hospitalizations, and 13 deaths.[3] Most of these cases involved acute respiratory and gastrointestinal problems. While these numbers may seem low relative to the U.S. population, there is consensus among experts that drinking-water associated infections are vastly underreported[4] and that outbreak surveillance data should not be used to estimate the actual number of outbreaks of waterborne disease.[3] While source water quality and inadequate drinking water treatment are partially responsible for such outbreaks,[4] aging water infrastructure, long water ages in distributions systems, especially in "shrinking cities",[5] and unintended consequences of water conservation

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measures, such as low-flow faucets and showers,[6] are also factors that contribute to poor water quality. These factors are not specifically targeted by current regulations under the U.S. Safe Drinking Water Act (SDWA), which employs a water treatment-centric approach for producing safe drinking water with a strong emphasis on monitoring contaminants of concern.[7] In contrast, the World Health Organization promotes a risk management framework approach, which is ideally applied from source water to the tap. This approach has been adopted, at least partially, by a number of countries, including Australia, New Zealand, Canada, and countries in the European Union.[4,7,8] An important first step towards exploring if the U.S. regulatory approach for microbiological drinking water concerns can be expanded to include multiple barrier treatment and management of distribution systems and building plumbing, is to understand historical and current compliance of microbiological drinking water regulations.

The U.S. Safe Drinking Water Act (SDWA) was passed by Congress in 1974 and compliance with national drinking water standards became effective on June 25, 1977. The SDWA, its 1986 and 1996 amendments, and associated regulations set legal limits (maximum contaminant levels [MCLs]) for more than 90 contaminants, treatment techniques, and monitoring and reporting schedules and methods.[9] The SDWA allows states to set their own drinking water standards as long as they are at least as stringent as those set by the SDWA.[10] As part of the SDWA, public water systems (PWSs) are required to regularly monitor contaminants in source waters, treated water, and in water collected from the distribution system. PWSs are defined as systems that deliver water for human use to at least 15 service connections or serve an average of at least 25 people for at least 60 days a year; they include public and privately owned water utilities.[11] The U.S. Environmental Protection Agency (EPA) classifies PWSs based on the number of people served. Very small systems serve 500 or fewer people, small systems serve between 501 and 3300 people, medium systems serve between 3301 and 10 000 people, large systems serve between 10 001 and 100 000 people, and very large systems serve more than 100 000 people. PWSs include approximately 50 000 community water systems (CWSs), which supply water to the same population throughout the year, and about 100 000 non-community water systems (NCWSs).[12] NCWSs are further divided into non-transient NCWSs (NTNCWSs), systems that regularly supply water to at least 25 of the same people at least six months per year (*e.g.*, schools, factories, office buildings, and hospitals with their own water systems), and transient NCWSs (TNCWSs), systems that provide water in places where people only stay for short periods of time (*e.g.*, gas stations and campgrounds with their own water source).[11] CWSs provide water to the majority of the U.S. population; 94% of the U.S. population received at least some of their water from a CWS in 2018.[13]

The Safe Drinking Water Information System (SDWIS) is a national database maintained by the U.S. EPA that catalogs SDWA violations in PWSs and makes these records available to the public.[14] PWSs are required to report SDWA violations to state, territory, or Native American tribal agencies (collectively referred to as primacy agencies), which subsequently provide this information to the U.S. EPA for inclusion in the SDWIS.[14] Some violations in the SDWIS are classified as health-based violations and include failures in treatment or operation of PWSs that can serve as indicators of risk to public health, such as exceeding the MCL for chemical contaminants (*e.g.*, arsenic, nitrate) and microbiological indicator organisms (*e.g.*, total coliforms), not complying with certain treatment techniques (*e.g.*, surface water treatment rule), and exceeding the maximum residual disinfectant level (MRDL). Acute health-based violations have the potential to cause immediate illness (*e.g.*, *Escherichia coli* MCL violation). Non-health-based violations include monitoring and reporting violations as well as public notification and other violations.[12] They do not have an immediate potential to cause illness, but may mask underlying health-based events since required monitoring or reporting was not performed by a PWS.

Few peer-reviewed studies have used the SDWIS to evaluate trends in health-based drinking water violations across the U.S. This may partially be due to the challenges of working with this database, but also because of its limitations (*e.g.*, underreporting of SDWA violations in SDWIS).[15,16] One recent study used the SDWIS to evaluate trends in health-based violations across the conterminous U. S. from 1982 to 2015 for CWSs serving more than 500 people.[17] This is one of very few studies that performed a nationwide evaluation of drinking water violations, and the only one that performed such a broad study for an extended time period. One of the motivations of this study was to develop strategies for identifying CWSs associated with violations to support better compliance of such systems.[17] The authors identified violation hotspots in several states, especially in the Southwest, and observed that those violation hotspots often had repeat violations. Further, they reported that violations were more common in rural areas compared to urban areas. They also observed that privately owned PWSs and PWSs that used a purchased water source had fewer violations than their counterparts. They justified their decision to include only CWSs that serve over 500 people because these PWSs cover a large fraction of the U.S. population; further very small CWSs and all NCWSs are required to sample less frequently than larger CWSs for some contaminants (*e.g.*, disinfection byproducts), which impacts the likelihood of detecting a violation, and are more likely to violate monitoring and reporting requirements.[17] Considering smaller CWSs may serve more low-income people in rural areas[18] and considering NCWSs provide water to vulnerable populations, such as those in schools and hospitals, we decided to include all CWS and NCWS in the current study. Two recent studies also covered both CWS and NCWS across the conterminous U.S., but only focused on nitrate violations from 1994–2016 (ref. 19) and arsenic violations from 2006–2017.[20] A similarly comprehensive study that includes all PWSs and focuses on microbiological health-based violations, *i.e.*, health-based violations of the total coliform rule (TCR) and revised total coliform rule (RTCR), is not yet available.

The U.S. EPA only requires regular microbiological monitoring for all PWSs for indicator bacteria, which are surrogates used to assess the potential presence of pathogenic microorganisms. Indicator bacteria targeted in drinking water monitoring include total coliforms and *E. coli*, a specific species of concern within the coliform group. Total coliform monitoring is used to evaluate the integrity of the distribution system and possible contamination, whereas the detection of *E. coli* suggests the presence of fecal contamination.[21] While exposure to bacteria within the total coliform group is not necessarily detrimental to human health, the presence of *E. coli* is more serious since several *E. coli* strains are pathogenic and their detection also suggests the likely presence of other fecal pathogens.[4] The total coliform rule (TCR), which was in effect from 1990 until April 1, 2016, required PWSs to monitor for these groups of indicator bacteria.[22] Violations of the TCR included health-based and non-health-based violations. Health-based violations in the TCR were triggered when a PWS exceeded the MCL for *E. coli* and for total coliforms.[23] The TCR was recently revised and microbiological monitoring for all PWSs is now regulated under the revised total coliform rule (RTCR), which became effective on April 1, 2016. In the RTCR, health-based violations are triggered when the *E. coli* MCL is exceeded and when PWSs do not complete assessments or corrective actions or when seasonal systems do not complete a state-approved start-up procedure.[24] Non-health-based violations for both the TCR and RTCR include a variety of violations that result from not complying with regulations related to monitoring, reporting, and public notification. While the TCR/RTCR applies to all PWSs, other microbiological regulations apply to PWSs depending on the source water, the type of treatment used, and the population served (*e.g.*, the groundwater rule, the surface water treatment rule and its amendments).[10]

To provide context for evaluating trends in microbiological drinking water quality violations, we first present long-term temporal trends of all health-based drinking water quality violations experienced by all PWSs in the conterminous U.S. We then show our evaluation of temporal trends in health-based microbiological violations covered under the TCR and RTCR for all PWSs. By providing these analyses for the various size categories of CWSs and for NCWSs, an initial evaluation of disparities in exposure to microbiological health-based violations became possible. We further evaluated health-based microbiological violations for all PWSs for different geographic regions in the conterminous U.S. Our temporal and geographic analyses provide background to assess concerns with microbiological drinking water regulations and suggest that targeted strategies focused on assisting PWSs with the highest risk for not being in compliance would have the greatest impact on public health.

2. Methods

Data were downloaded from the U.S. EPA's SDWIS (ref. 25) and analyzed using Python software and the Python library Pandas. Only PWSs that report to a state primacy agency in the conterminous U.S. were included. PWSs with a primacy agency type of 'territory' or 'tribal' were not included because these communities have experienced injustices related to water quality and often face administrative challenges and therefore deserve to be studied separately.[18,26]

Using the SDWIS, all health-based violations data were downloaded, which includes health-based violations of over 90 contaminants. In the advanced search options of the SDWIS, year was set to '2020', quarter was set to '1', activity status was set to 'All', and is health based was set to 'Yes'. The remainder of parameters were left as the default. Because the SDWIS limits downloads to 150 000 rows, health-based violations were downloaded in four separate files, and later combined into one dataset using Python.

In the 'Violations' table of SDWIS, TCR and RTCR health-based violations were downloaded separately. In the advanced search options of the SDWIS, all parameters were selected to be the same as above, except that rule was set to 'Total Coliform Rule' or 'Revised Total Coliform Rule.' Again, because the SDWIS limits downloads to 150 000 rows, TCR violations were downloaded in two separate files, and later combined into one dataset using Python.

The SDWIS data on population served by PWSs are occasionally updated. Therefore, we assumed in our analyses that the population served by a PWS at the time of a violation was the same as the corresponding population in the most recently updated version of the SDWIS (2020 quarter 1). Additionally, when a PWS becomes inactive or when it becomes a non-public system, the population served is occasionally set to 0. All records for which the population served was 0 were removed from our analysis.

The SDWIS provides a start and end date for each violation. In some cases, the end date of the violation was missing. The SDWIS also provides a compliance status for each violation. If the compliance status for a violation with a missing end date was 'Open', we assumed that the violation continued through 2019. If the compliance status for a violation with a missing end date was anything besides 'Open', we assumed the violation ended in the same year that it began.

3. Results and discussion

3.1 Temporal trends in health-based drinking water violations

The number of health-based violations in PWSs are shown per year from 1978 to 2019 (Fig. 1). We selected 1978 as the first year to show data because compliance with national drinking water standards became effective on June 25, 1977 (ref. 27) and 1978 is thus the first complete year that SDWA health-based violations were reported. Results are organized by contaminant/rule (Fig. 1a), PWS size (Fig. 1b), and PWS type (Fig. 1c).

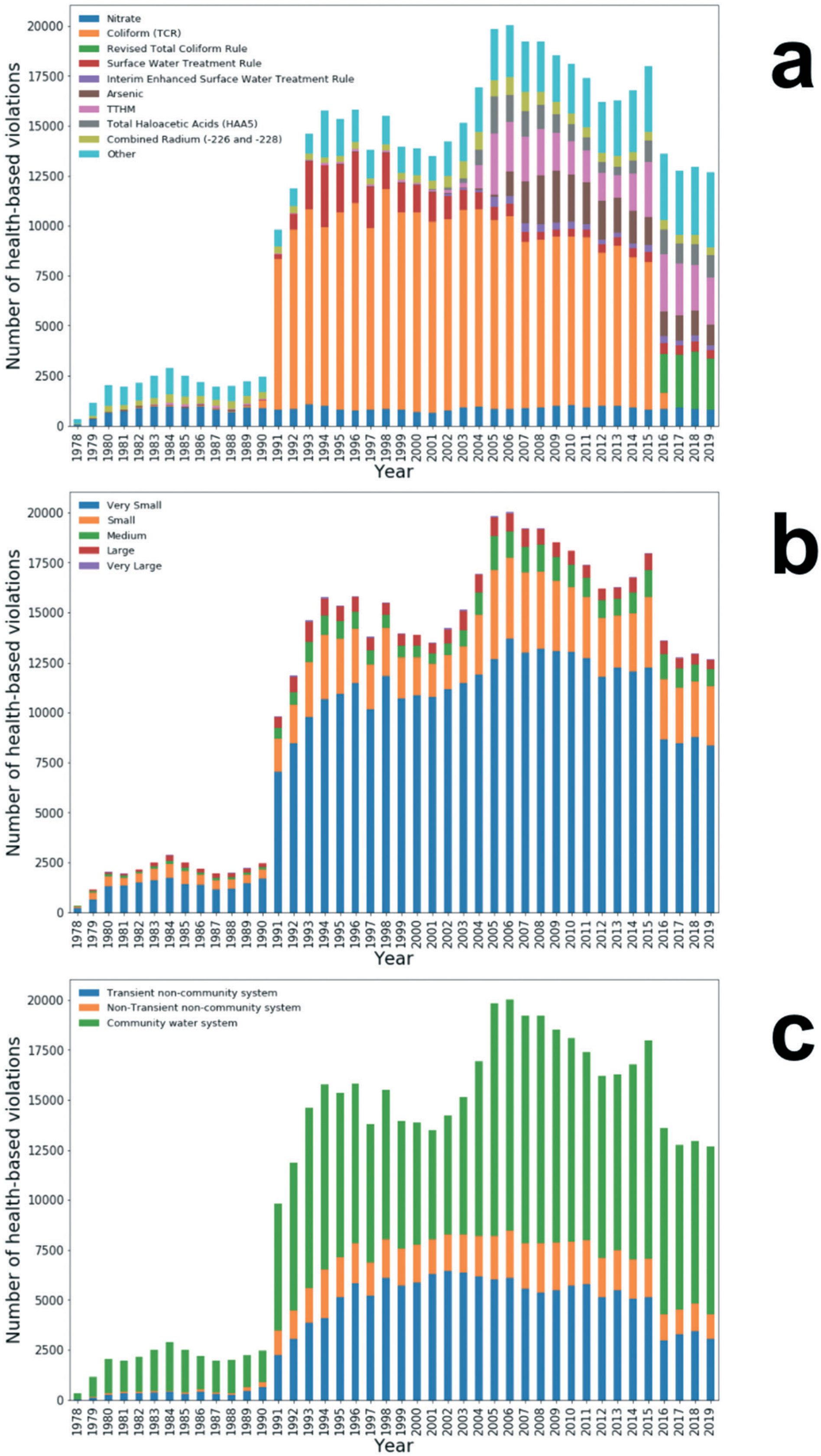

Fig. 1 Number of health-based violations per year in U.S. PWSs with state as primacy agency, excluding Alaska and Hawaii. (a) The nine contaminants/rules with the most health-based violations (the name of the rule or contaminant is reported as given in the SDWIS under the category "contaminant name") and all other health-based violations combined (indicated as "other" in the legend) are plotted. (b) Health-based violations are shown for different PWS sizes. (c) Health-based violations are shown by PWS type.

Even though TCR health-based violations cover only 26 years out of the 42 years of SDWA violations reported in Fig. 1, they have been the most common type of health-based violation (Fig. 1a), with a total of just over 230 000 violations (51.5% of all health-based violations). Since the TCR became effective on December 31, 1990,[28] the total number of all health-based violations increased dramatically in 1991. After the TCR was revised to the RTCR in April 2016, the number of health-based violations decreased substantially. We discuss TCR related health-based violations and explore how the change from TCR to RTCR impacts temporal trends in the number of overall health-based violations in more detail in the next section.

Table 1 lists the nine contaminants/rules responsible for the greatest number of health-based violations for the period 1978–2019 (Fig. 1a) with the years the relevant regulations became effective. In addition to the TCR and RTCR, other rules with high numbers of health-based violations include the surface water treatment rule and the interim enhanced surface water treatment rule. Contaminants with high numbers of health-based violations include nitrate, arsenic, total trihalomethanes (TTHM), total haloacetic acids (HAA5), and combined radium. Temporal changes in the number of violations for these two rules and four contaminants and how they contribute to the overall number of health-based violations are briefly discussed below. Note that violations for certain contaminants/rules sometimes appear before the regulations become effective. This can happen because regulations typically are promulgated three years before they become effective and some PWSs start reporting violations early.

Temporal trends in the number of health-based violations can be attributed to the implementation of new regulations, enforcement capacity of the primacy agency, source water quality, and PWS treatment capabilities.[17] Our analysis suggests that regulatory changes and the subsequent response of PWSs are important drivers for the observed temporal trends in the number of health-based violations (Fig. 1a). Several contaminants have been regulated since 1977, when the SDWA became effective, although standards were less strict for some of these contaminants during those early years. After an initial gradual increase from 1978 to 1984, likely related to an improvement in reporting during the early years of the SDWA, the number of nitrate violations slowly decreased. A relatively small increase was observed in 1993 when the required sampling frequency for groundwater systems increased, but further improvements remained limited (Fig. 1a).[19]

Combined radium violations also appeared from the start of the time period included in Fig. 1a and, after an initial gradual increase, their numbers did not change much until 2003 when the radionuclides rule became effective and a more substantial increase was observed (Fig. 1a). The radionuclides rule did not change the MCL for combined radium, so the increase in the number of combined radium violations was caused by other factors, such as the availability of improved analytical methods for radionuclides or improved reporting after implementation of the radionuclides rule. The number of combined radium violations gradually decreased starting in 2008.

Very few arsenic violations were incurred until 2006, when the arsenic rule became effective.[20] The increase in arsenic violations contributed to the rise in overall health-based violations observed for that year. The number of arsenic violations increased for another two years and then began to decrease gradually (Fig. 1a).

The number of TTHM and HAA5 violations increased substantially starting in 2002/2004 when the stage 1 D/DBP rule became effective (the effective date depends on PWS characteristics) through 2005, and then gradually decreased until 2013 (Fig. 1a). TTHM and HAA5 violations increased again starting in 2014, after the stage 2 D/DBP rule had become effective (Table 1), followed by a slow improvement through the end of the reporting period. The changes in numbers of TTHM and HAA5 violations were substantial and contributed to the observed changes in the overall number of health-based violations from 2002 to 2015.

Table 1 Year the regulations for which the corresponding violations are reported in Fig. 1a became effective

Rule/regulation	Year the regulation became effective	"Contaminant name"[a]
NIPDWR[b]	1977	Nitrate
NPDWR[c]	1993	
Total coliform rule	1990	Coliform (TCR)
Surface water treatment rule	1993	Surface water treatment rule
Interim enhanced surface water treatment rule	2002	Interim enhanced surface water treatment rule
NIPDWR	1977	Combined radium (−226 and −228)
Radionuclides rule	2003	
TTHM rule	1981/1983	TTHM
Stage 1 D/DBP[d] rule	2002/2004	
Stage 2 D/DBP rule	2012/2013	
Stage 1 D/DBP rule	2002/2004	Total haloacetic acids (HAA5)
Stage 2 D/DBP rule	2012/2013	
NIPDWR	1977	Arsenic
Arsenic rule	2006	
Revised total coliform rule	2016	Revised total coliform rule

[a] The name of the rule or contaminant is reported as given in the SDWIS under the category "contaminant name". [b] NIPDWR = National Interim Primary Drinking Water Regulations. [c] National Primary Drinking Water Regulations. [d] Disinfectants and disinfection byproducts.

Surface water treatment rule violations first appeared in 1991, their numbers increased drastically in 1993, the year the rule became effective (Table 1), peaked in 1994, and then very slowly decreased throughout the rest of the reporting period. The initial substantial rise in 1993 contributed to the increase in overall health-based violations observed for that year. Interim enhanced surface water treatment rule violations first appeared in 2002, when the regulation became effective (Table 1), peaked in 2005, then gradually decreased.

PWSs may take time to respond to new regulations by needing to upgrade treatment systems, implement new treatment strategies, or access different source waters. Therefore, as observed for several of the contaminants/rules, it often takes considerable time before the number of violations decreases after a new regulation becomes effective (Fig. 1a). Decreases in the number of violations may also be due to improvements in source water characteristics due to external factors, such as reductions in arsenic releases from the chemical and hazardous waste sectors into the environment.[20]

Since the U.S. EPA classifies PWSs based on the number of people served, it is informative to evaluate the number of health-based violations by PWS size. As illustrated in Fig. 1b, very small PWSs contributed most health-based violations, and the numbers of reported health-based violations decreased with increasing system size. To put this in perspective, we determined the population served for the different PWS size categories using data most recently made available in the SDWIS (2020, quarter 1). Very small PWSs (500 or fewer people) served 13.25 million people, small PWSs (between 501 and 3300 people) served 23.69 million people, medium PWSs (between 3301 and 10 000 people) served 29.83 million people, large PWSs (between 10 001 and 100 000 people) served 111.49 million, and very large PWSs (more than 100 000 people) served 143.88 million. This analysis indicates that very small, small, and medium PWSs serve fewer people than large and very large PWSs, thus the disproportionately large number of violations for smaller PWSs may not have the same impact when analyzed on a per person basis. Note that it is difficult to determine how many people are impacted by a violation for a number of reasons. For example, people may be counted more than once if they are served by more than one PWS (*e.g.*, a person living in a home served by a CWS and attending a school with a NCWS). Furthermore, not all people served by a PWS are necessarily impacted by a violation, especially for larger PWSs that maintain large distribution systems with several sampling locations used for compliance monitoring.

In addition to classifying PWSs by size, the U.S. EPA differentiates PWSs based on whether they (i) serve the same population throughout the year (CWSs), (ii) regularly supply water to at least 25 of the same people at least six months per year (NTNCWSs), and (iii) provide water in places where people only stay for short periods of time into (TNCWSs).[11,12] Fig. 1c shows that the number of health-based violations incurred by all three PWS types dramatically increased in 1991 due to the introduction of the TCR. Subsequently, the health-based violations incurred by NCWSs (TNCWSs and NTNCWSs) increased, then remained relatively constant until 2015. After implementation of the RTCR in 2016, NCWS health-based violations dropped substantially, primarily due to a decrease in health-based coliform violations (Fig. 1a). In contrast, while CWS health-based violations also increased during the first few years of the TCR (starting from 1991), they subsequently decreased from 1995 to 2001 and increased again from 2002 to 2005. After 2005, CWS health-based violations gradually decreased and had leveled off by 2019 although there was an uptick in 2014, 2015, and 2016 caused primarily by higher numbers of TTHM violations (Fig. 1a). Clearly, large swings in total health-based violations were primarily caused by changes in the numbers of CWS health-based violations, while NCWS numbers stayed relatively constant. Due to the temporal changes in CWS health-based violations, the contribution of NCWS health-based violations to all health-based violations varied from 35% in 1991, to just under 60% in 2001, to 34% in 2019.

3.2 Temporal trends in health-based microbiological drinking water violations

The TCR, which became effective on December 31, 1990,[28] was recently revised and microbiological drinking water regulations that apply to all PWSs are now covered under the RTCR, which became effective on April 1, 2016. Evaluating how this change in regulation has impacted trends in health-based violations was an important objective of this study. The TCR triggered a health-based violation when the MCL for *E. coli* (violation code 21 in SDWIS) or total coliforms (violation code 22 in SDWIS) was exceeded.[23] It is important to note that, for smaller PWSs taking fewer than 40 samples per month, a single total coliform-positive sample triggered a total coliform violation, while violations for PWSs collecting 40 or more samples were triggered when more than 5.0% of samples were total coliform-positive. Under the RTCR, health-based violations are not directly impacted by total coliform numbers; they are triggered only when the *E. coli* MCL is exceeded (violation code 1A in SDWIS)[22] and when treatment technique violations, including assessments, corrective actions, or a state-approved start-up procedure, are not completed (violation codes 2A, 2B, 2C, 2D in SDWIS).[24] Assessments under the RTCR can be triggered in various ways. For example, an assessment can be triggered in the same way total coliform MCL violations were triggered under the TCR (greater than 5.0% total coliform-positive samples for larger systems and a single total coliform-positive sample for smaller systems). Note that under the RTCR, triggering this assessment does not necessarily constitute a violation, but failure to complete the assessment or failure to correct sanitary defects constitutes a violation. We performed a temporal analysis (1991–2019) for health-based TCR and RTCR violations in PWSs, separated by health-based coliform violations (Fig. 2) and *E. coli* violations (Fig. 3), further organized by PWS size (Fig. 2a and 3a) and PWS type (Fig. 2b and 3b). We also evaluated the transition years from TCR to RTCR by examining the distribution of the number of health-based coliform violations and *E. coli* related violations for 2015 and for 2017, by PWS size and by PWS type (Table 2). Note that while the data for the transition years are provided in Table 2, they do not necessarily represent long term trends. Rather, Table 2 offers insights into the immediate impacts of the implementation of the RTCR.

3.2.1 Health-based coliform violations during the TCR and RTCR. As indicated above, the TCR triggered a health-based coliform violation when the MCL for *E. coli* (violation code 21) or total coliforms (violation code 22) was exceeded.[23] In contrast, in the RTCR, health-based coliform violations are not directly impacted by total coliform numbers; they are triggered only when the *E. coli* MCL is exceeded (violation code 1A)[22] and when assessments, corrective actions, or a state-approved start-up procedure are not completed (violation codes 2A, 2B, 2C, 2D).[24] Health-based coliform violations made up the largest fraction of all health-based violations for the majority of the years for which data are reported (Fig. 1a). While this observation could suggest that health-based coliform violations have been one of the greatest drinking water quality concerns, it does not take into account the frequency with which different contaminants need to be monitored, the duration of violations or how many compliance issues occurred within a single violation reporting period, the severity of the issue that led to the violation, and the public health impact of a violation. Different contaminants are monitored with varying frequencies depending on a number of factors including the

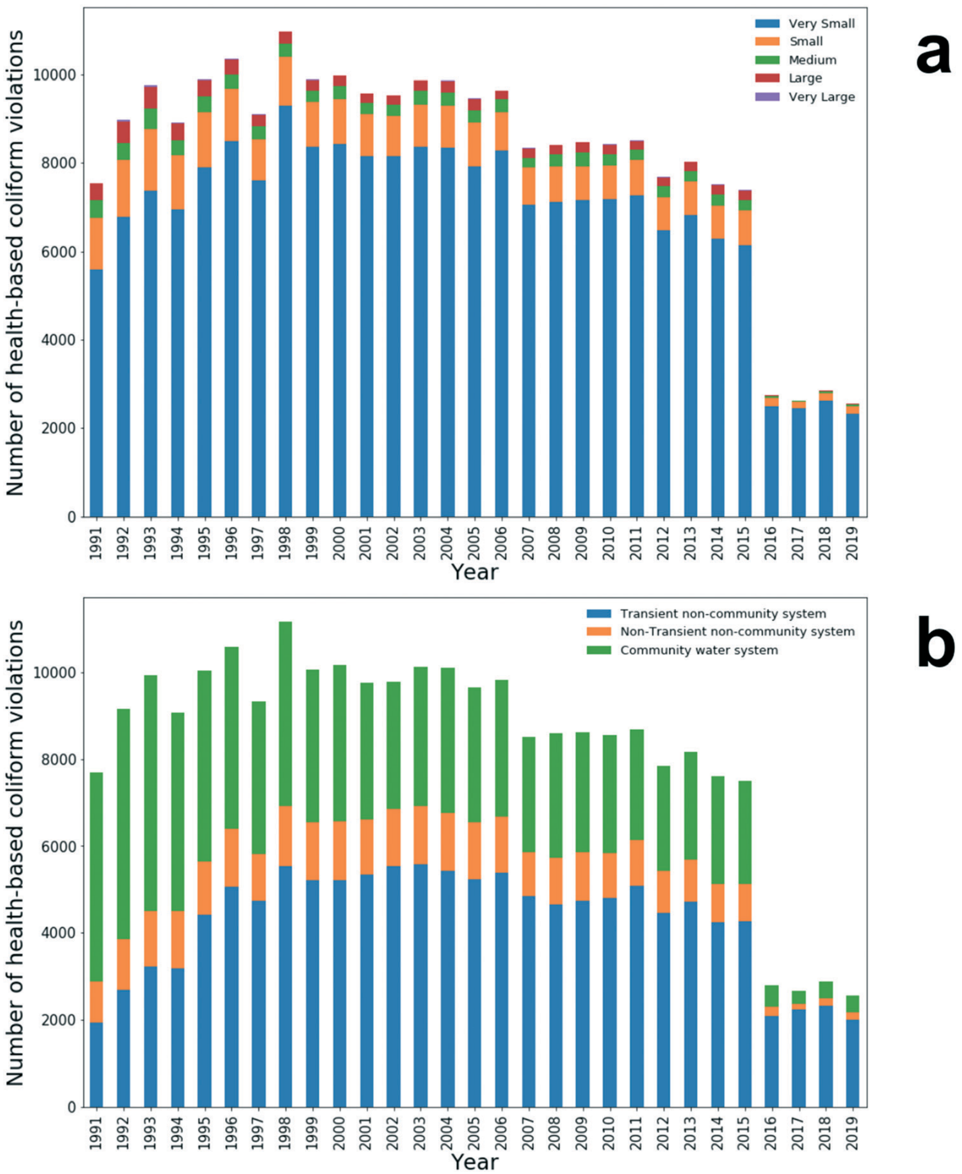

Fig. 2 Number of health-based coliform violations per year in U.S. PWSs with state as primacy agency, excluding Alaska and Hawaii, shown by (a) PWS size and (b) PWS type.

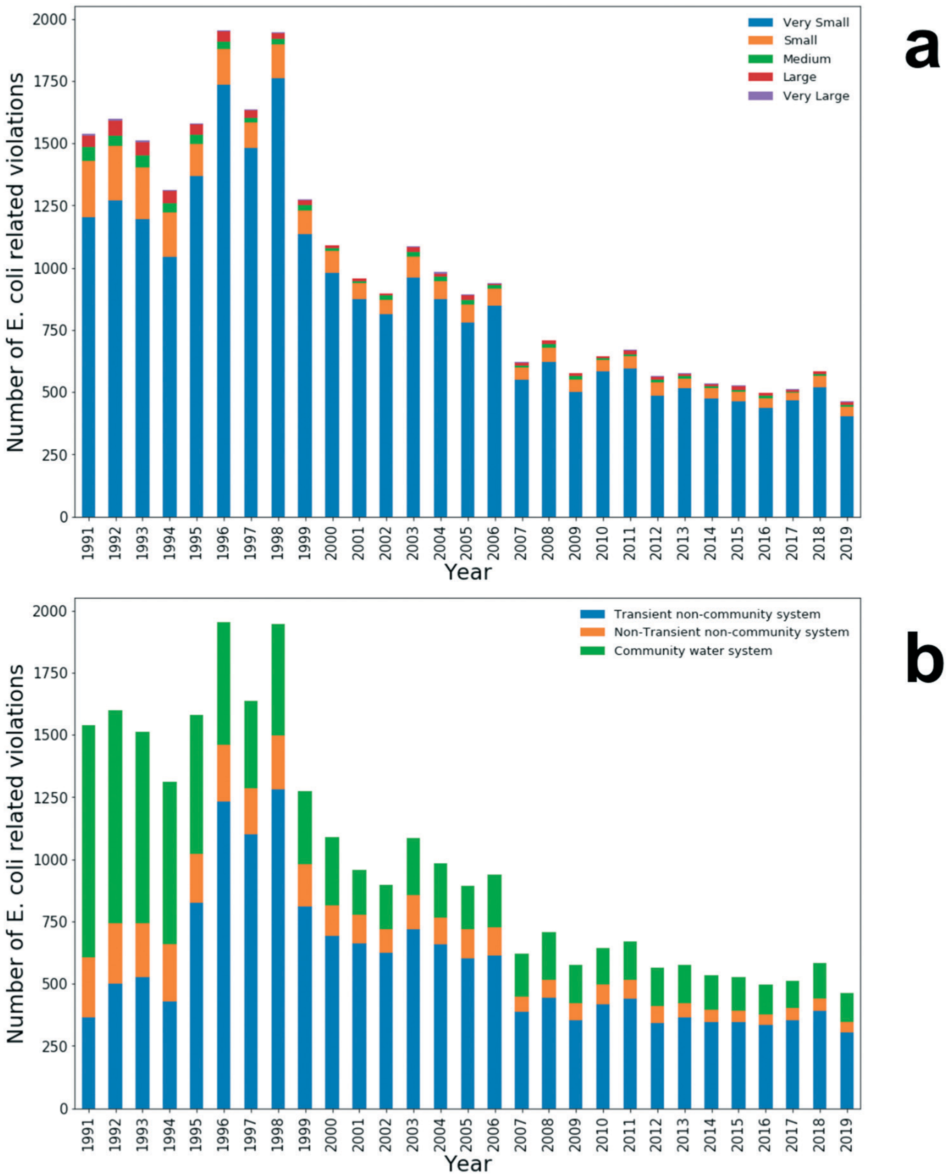

Fig. 3 Number of *E. coli* related violations (violation codes 21 and 1A in the SDWIS) per year in U.S. PWSs with state as primacy agency, excluding Alaska and Hawaii, shown by (a) PWS size and (b) PWS type.

likelihood that the concentration of the contaminant changes over time. For example, the TCR required PWSs to report violations on a monthly basis,[29] whereas contaminants like arsenic are required to be monitored on a quarterly or annual basis (compliance is based on a running annual average) because their concentrations are less likely to vary over time.[30] As a result, even if a PWS is continuously out of compliance for arsenic, it may only have one MCL violation per year. Furthermore, the duration of a violation may span an entire compliance monitoring window, be resolved immediately, or even occur multiple times. For example, regardless of how many times in a single month a PWS measured a positive total coliform result, that system would only have one health-based coliform violation for that month's reporting period.

The high frequency of health-based coliform violations compared to the lower frequency of other health-based violations may give the impression to the general public that the greatest attention should be paid to eliminating health-based coliform violations. The U.S. EPA started evaluating this issue about a decade ago[31] and called into question whether the monthly reporting requirement for total coliform violations under the TCR as health-based violations was resulting in an erosion in consumer confidence.[29] Although these violations were classified as health-based violations and required public notice, they may not be of immediate concern for consumers as discussed above. The above considerations were taken into account when the TCR was reviewed in accordance with SDWA policy. To address the apparent discrepancy that certain health-based TCR violations were not

Table 2 Distribution of all active PWSs with state as primacy agency, excluding Alaska and Hawaii, by PWS size and type in 2015 and 2017, and distribution of the health-based coliform violations and *E. coli* related violations for 2015, the last complete year the TCR was in place, and for 2017, the first complete year the RTCR was in effect, by PWS size and type

	Very small (<500 people)	Small (between 501 and 3300 people)	Medium (between 3301 and 10 000 people)	Large (between 10 001 and 100 000 people)	Very large (>100 000 people)	CWS	NCWS	
							NTNCWS	TNCWS
Percentage of active PWSs[a]								
2015	81.1	12.5	3.5	2.6	0.3	33.4	11.8	54.9
2017	80.9	12.6	3.5	2.7	0.3	33.6	11.8	54.7
Percentage of health-based coliform violations[b]								
2015 (TCR)	**83.1**	10.7	3.2	**2.9**	0.1	31.6	11.5	**56.8**
2017 (RTCR)	**92.9**	5.7	0.7	0.5	0.1	11.0	5.2	**83.7**
Percentage of *E. coli* related violations[b]								
2015 (TCR)	**88.0**	7.6	1.0	**3.0**	**0.4**	25.5	8.6	**65.9**
2017 (RTCR)	**91.6**	5.5	1.2	1.2	**0.6**	21.5	9.4	**69.1**

[a] Percentage of active PWSs calculated from SDWIS using quarter four data for each year. [b] Bold fields indicate PWS types or size categories that incurred a higher percentage of violations than the corresponding percentage make up of active PWSs for the designated year.

of immediate public health concern, along with other considerations,[31] the U.S. EPA replaced the TCR with the RTCR, which no longer requires that total coliform positive results are reported as health-based violations. While RTCR health-based violations occur less frequently, they are believed to be better indicators for public health risk.[31]

Fig. 1 and 2 show that after the implementation of the RTCR in 2016, the number of health-based coliform violations decreased drastically. As discussed above, this reduction had been anticipated by the U.S. EPA and does not necessarily imply that microbiological water quality improved after 2016. Analyzing the temporal trend of *E. coli* violations (Fig. 3) provides a more accurate assessment of microbiological water quality as the presence of *E. coli* may have direct implications for human health. *E. coli* violations remained relatively constant for the past ten years, including after the implementation of the RTCR. This analysis suggests that the implementation of the RTCR so far has not resulted in improved microbiological water quality. The RTCR's requirement to report treatment technique violations (incomplete assessments, corrective actions, or a state-approved start-up procedure) has the potential to improve microbiological water quality, but the impact of these requirements cannot yet be evaluated using SDWIS. Future studies could be designed to evaluate whether the integration of treatment technique violations in the RTCR eventually result in reduced *E. coli* violations over time as well as contribute to overall improved microbiological water quality as indicated by other measures, including alternative indicators (*e.g.*, heterotrophic plate count [HPC], certain human viruses) and opportunistic pathogens (*e.g.*, nontuberculous mycobacteria).[4] With improved reporting of outbreaks, drinking water associated *E. coli* outbreak data can be utilized to evaluate the true impact of this rule change.

3.2.2 Disparities in health-based coliform violations by PWS size and type. Our analysis of temporal trends in health-based coliform violations by size indicated that very small PWSs, those serving 500 or fewer people, accounted for the vast majority of all health-based coliform violations (Fig. 2a). In fact, very small PWSs accounted for more health-based coliform violations than all other PWS types combined in each year from 1991 to 2015, when the TCR was in effect. This trend was unaffected by the implementation of the RTCR in 2016, even though the numbers of health-based coliform violations for all PWSs decreased considerably at

Table 3 Distribution of active U.S. PWSs by PWS size and type for 2020 quarter 1 (U.S. PWSs with state as primacy agency, excluding Alaska and Hawaii)

	CWS	NTNCWS	TNCWS	Total
Very small	25 979	14 664	75 132	**115 775**
Small	12 941	2331	2937	**18 209**
Medium	4921	145	74	**5140**
Large	3856	27	12	**3895**
Very large	435	1	1	**437**
Total	**48 132**	**17 168**	**78 156**	**143 456**

that time as discussed above. However, since the number of violations proportionally dropped less for very small PWSs than for other PWSs, they accounted for an even greater percentage of the health-based coliform violations after implementation of the RTCR. Specifically, the percentage of health-based coliform violations for very small PWSs increased from 83.1% in 2015 to 92.9% in 2017 (Table 2). Table 3 provides the distribution of PWSs by size and type to better interpret the results shown in Table 2.

The number of *E. coli* related violations was approximately an order of magnitude lower (Fig. 3a) than the number of health-based coliform violations (Fig. 2a), and there was a greater decrease in the number of *E. coli* related violations with time. Specifically, the total number of *E. coli* related violations declined substantially from just over 1500 to about 460 per year from 1991 to 2019. The introduction of the RTCR did not greatly change the number of *E. coli* related violations. In 2015, the year before the RTCR was implemented, there were 525 *E. coli* related violations. In 2017, the year after the RTCR was implemented, there were 511 *E. coli* related violations. Note that the substantial decrease observed in 2019 is potentially misleading as violations may continue to be added to SDWIS several quarters after the end of a calendar year. Very small PWSs also were responsible for the majority of all *E. coli* related violations.

Considering the number of very small PWSs is much greater than any other size category of PWSs, their greater contribution to the total number of health-based coliform and *E. coli* related violations was not surprising. A previous study performed a similar analysis for fiscal year 2013, when the TCR was in effect, and reported that the percentage of PWSs with health-based TCR violations was 4% for very small, 3% for small, 4% for medium, and 4% for large PWSs, but that this percentage was only 1% for very large PWSs.[32] Those data suggest that very small PWSs do not have a disproportionately high number of violations under the TCR. They further indicated that TCR monitoring and reporting violations, which are non-health-based violations, were observed at a greater percentage for smaller systems, suggesting that disparities for very small PWSs may nevertheless exist.

To further evaluate the possible occurrence of disparities, we compared the distribution of PWSs by size to the distribution of health-based coliform violations and *E. coli* related violations for 2015, the last year the TCR was in effect, and for 2017, the year after the RTCR was implemented (Table 2). This analysis indicates that very small PWSs contributed marginally higher percentages of health-based coliform violations when compared to the percentage of very small PWSs among all PWSs in 2015 (83.1% of violations compared to 81.1% makeup) and this slight disparity increased in 2017 (92.9% of violations compared to 80.9% makeup). Only large PWSs also had a slightly higher percentage of health-based coliform violation compared to the percentage of large PWSs among all PWSs in 2015 (2.9% of violations compared to 2.6% makeup), but this value decreased dramatically after the implementation of the RTCR in 2017 (0.5% of violations compared to 2.7% makeup).

The analysis for *E. coli* related violations indicated that very small and large PWSs slightly worsened and substantially improved, respectively, relative to the percent makeup of active PWSs after implementation of the RTCR. Specifically, very small PWSs contributed 88.0% of *E. coli* related violations compared to 81.1% makeup in 2015, and the corresponding numbers were 91.6% and 80.9% in 2017. Large PWSs incurred a slightly higher percentage of *E. coli* related health-based violations compared to the percentage of large PWSs among all PWSs in 2015 (3.0% of violations compared to 2.6% makeup), but this value decreased dramatically after implementation of the RTCR in 2017 (1.2% of violations compared to 2.7% makeup). Surprisingly, very large PWSs had a disproportionately high percentage of *E. coli* related health-based violations in 2017 (0.6% of violations compared to 0.3% makeup), whereas before the implementation of the RTCR these percentages had been more similar (0.4% of violations compared to 0.3% makeup).

This comparison of the distribution of PWSs by size with the distribution of health-based coliform violations and *E. coli* related violations suggests that very small PWSs did not fare as well under the RTCR as they did under the TCR. Very small PWSs were responsible for the majority of all *E. coli* related violations throughout the reporting period and their relative contribution to the total number of *E. coli* related violations increased with time, indicating they incur a disproportionate burden of health-based microbiological violations. Allaire *et al.*[17] suggest that the greater drinking water quality regulation non-compliance observed for smaller PWSs directly or indirectly relates to the more limited financial capacity of those utilities. This observation helps explain the disparity we observed for very small PWSs but does not explain why the disparity worsened substantially after the implementation of the RTCR. Our observation that large PWSs improved and very large PWSs worsened in terms of health-based coliform violations also needs further investigation. Even though large and very large PWSs represent only 2.6% and 0.3% of active PWSs in 2015, even small changes in their numbers of violations have the potential to affect many more people compared to smaller PWSs. It is especially concerning that very large PWSs were overrepresented in *E. coli* violations. A 0.1% difference in 2015 and 0.3% difference in 2017 may seem small, but potentially affects a large fraction of the population.

Our analysis of the number of health-based coliform violations by PWS type also indicated unequal distributions. The numbers of health-based coliform violations incurred by TNCWSs increased drastically from 1991 to 1998, then leveled off, and decreased after implementation of the RTCR (Fig. 2b). TNCWSs accounted for 25% of health-based coliform violations in 1991, 57% in 2015, and 84% in 2017. While the numbers of TNCWS violations increased initially, after 1998, the increase in the percentage of TNCWS violations was due to a decrease in the numbers of CWS violations (Fig. 2b). Similar to very small PWSs, the percentages of health-based coliform violations for TNCWS in 2015 was comparable to the makeup of TNCWS among all PWSs (56.8% of violations compared to 54.9% makeup) but worsened with the transition to the RTCR (83.7% of violations compared to 54.7% makeup). It is important to note, however, that because of how PWS types are defined, TNCWSs are almost exclusively responsible for health-based violations related to seasonal startup procedures (violation code 2D in SDWIS). Even without including these violations in the analysis, TNCWSs still accounted for 75.0% of health-based violations in 2017.

TNCWS were responsible for the majority of *E. coli* related violations for most of the reporting period (Fig. 3b). During the early years of the TCR, *E. coli* related violations were incurred more frequently by CWS, but those numbers decreased drastically within a few years. As early as 1995, the majority of *E. coli* related violations were incurred by TNCWS. Unlike with health-based coliform violations, the distribution of *E. coli* related violations by PWS type did not change much from 2015 to 2017, but the burden incurred by TNCWS was disproportionate (Table 2). Specifically, the percentage of *E. coli* violations for TNCWS in 2015 was 65.9%, whereas the makeup of TNCWS among all PWSs was 54.9%. The corresponding values were 69.1% and 54.7% for 2017.

Our analysis of the health-based coliform and *E. coli* related violations by PWS size and type points to a disproportionate burden for very small PWSs and for TNCWSs and that this burden worsened after the implementation of the RTCR, especially for health-based coliform violations. Moreover, the fact that certain small and very small PWSs may be eligible for reduced frequency of monitoring means that when an MCL violation is incurred, consumers may have been impacted for a prolonged period of time. These results, combined with the data presented in Table 3, suggest that it would be informative to consider PWS size and type together when analyzing violations and possible solutions. Specifically, very small TNCWSs represent 52.4% of all PWSs, whereas very small CWSs constitute the second largest group making up 18.1% of all PWSs. While a detailed analysis of violations by combining PWS size and type is beyond the scope of this study, it is clear that focusing on very small TNCWSs when aiming to reduce RTCR violations would be a productive strategy as these likely bear the brunt of violation disparities.

It is unclear what our findings may mean for very small PWSs and TNCWSs in terms of the burden they bear to address drinking water quality violations moving forward and changing the support they need to improve public health outcomes. It may be argued that the increased disparity after RTCR implementation could improve visibility for very small PWSs and TNCWSs that need more support to improve compliance. Our analysis further suggests that the change from TCR to RTCR allowed for existing disparities among PWSs to be highlighted more clearly. On the other hand, we note that large disparities were already observable when considering only *E. coli* violations, which are inherently tied to potential public health risk. The disparities related to *E. coli* violations did not change much after implementation of the RTCR, which makes sense given that the *E. coli* violation regulations only changed to a limited extent. However, we hope that the implementation of the RTCR eventually results in the intended outcomes of fewer *E. coli* violations and better microbiological water quality, but more time may be needed to achieve these effects.

The large change in the distribution of health-based coliform violations from 2015 to 2017 for both very small PWSs and for TNCWSs, combined with a smaller change in the corresponding distribution for *E. coli* related violations, suggests that very small TNCWSs may be particularly prone to incurring treatment technique violations in the RTCR (violation codes 2A, 2B, 2C, 2D in SDWIS). This suggestion needs to be explored in future research when additional RTCR data become available. If confirmed, it would be important to focus on providing greater resources and technical assistance to TNCWS to specifically address the completion of assessments, corrective actions, and state-approved start-up procedures.[24]

3.3 Geographic trends in health-based microbiological drinking water violations

We performed a geographic analysis of health-based coliform violations within the TCR and RTCR for all PWSs for the same time period considered above for the temporal analysis (1991–2019). The results are summarized by showing the total number of violations by state for three time windows (Fig. 4). We observed substantial variability in the numbers of health-based coliform violations for different states and regions of the U.S. during these three periods. From 1991 to 2000 (Fig. 4a), Ohio had the greatest number of health-based coliform violations (10 661); Washington and Wisconsin were the only other states with more than 5000 violations (6512 and 5544, respectively).

For the next time window (2001–2010), states in the Great Lakes region still exhibited high numbers of health-based coliform violations relative to states in other regions. Specifically, Ohio, Pennsylvania, Wisconsin, Indiana, and Michigan were among the seven states with the most violations (6010, 4780, 4617, 3994, and 3979, respectively). During this time period, California had the most health-based coliform violations (6092). Missouri also experienced high numbers of violations (5187) relative to other states.

During the period from 2011 to 2019, Pennsylvania (5169) and California (3265) were the states with the most health-based coliform violations. The five Great Lakes region states previously mentioned remained in the top eight states with the most health-based coliform violations. It is important to note that this period is shorter than the other two time windows, and that the RTCR was implemented during this period. Both the shorter period of time and the substantial decrease in violations upon transitioning to the RTCR (Fig. 2) contributed to the lower number of violations reported for each state during this time window.

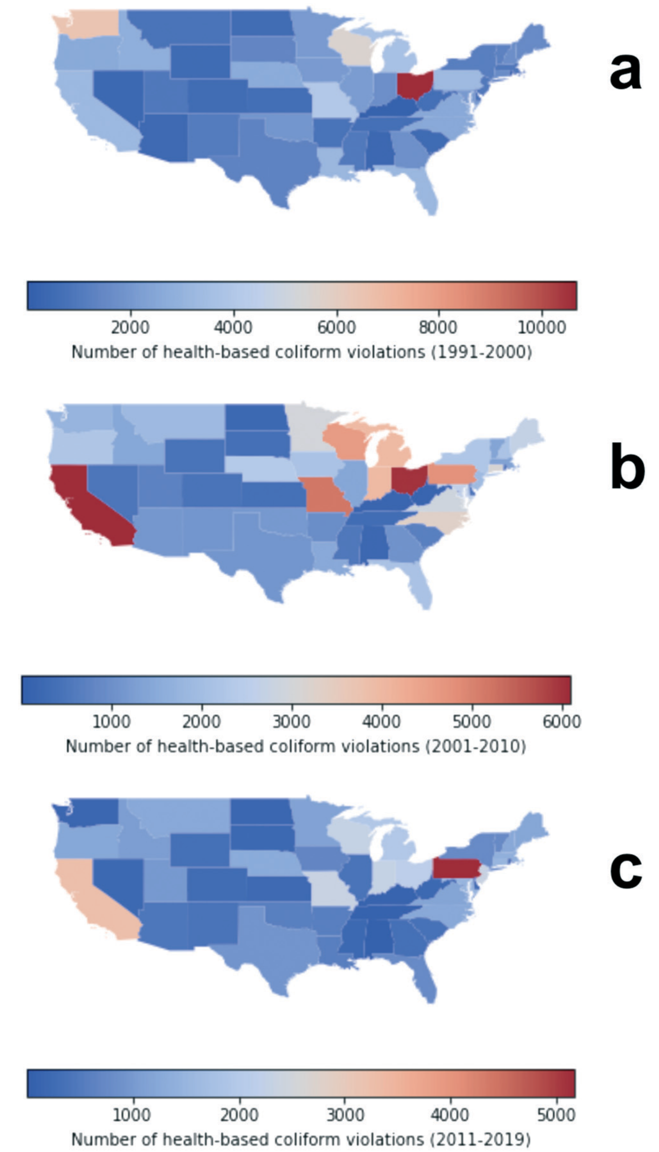

Fig. 4 Number of health-based coliform violations by state (a) 1991–2000, (b) 2001–2010, and (c) 2011–2019. Note that the color scale is relative to magnitudes for individual plots.

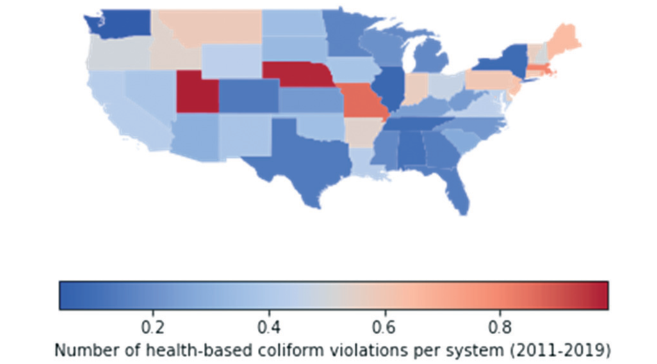

Fig. 5 Number of health-based coliform violations per PWS by state from 2011 to 2019. Note that the normalization per PWS was performed using the number of active PWSs for 2015.

While this geographic analysis is informative and indicates that states in the Great Lakes region and California had the greatest number of health-based coliform violations throughout the time period analyzed (1991–2019), it would be helpful to also take into account the population served by PWSs as well as the number of PWSs per state, not just the total number of violations per state. However, as discussed above, the value of using the population served is diminished as the number of people impacted by a PWS in violation is not necessarily the same as the number of people served by a PWS in violation. Normalizing the number of violations per PWS is not directly possible for each of the three time periods because SDWIS only includes the number of active PWSs from 2013 onward. To approximate the number of health-based violations per PWS for each state for the period 2011–2019, we normalized the total number of health-based violations per state by the number of active PWSs in the corresponding state for 2015. Since the number of active PWSs only changes slowly over time (the number of active PWSs decreased 3.3% from 2013 to 2019), using the number of active PWSs for 2015 (the year halfway between 2011 and 2019) provides a good solution to perform this normalization. The results are presented in Fig. 5 and indicate that the geographic distribution using this normalization was quite different from the one presented in Fig. 4c. Utah, Nebraska, and Missouri had the highest number of health-based violations per PWS over this time period (0.99, 0.97, and 0.86, respectively). The Great Lakes region, which had high numbers of total violations for the five states indicated above, Pennsylvania, Wisconsin, Indiana, Ohio, and Michigan (listed in decreasing order of occurrence of total violations; Fig. 4c), did not see particularly high numbers of violations per PWS. For example, Pennsylvania, which had the highest number of total violations (Fig. 4c), only had the tenth highest number of violations per PWS. The normalized values for Pennsylvania, Indiana, Ohio, Wisconsin, and Michigan were 0.60, 0.57, 0.47, 0.20, and 0.18, respectively. This apparent discrepancy is, in part, because states in this region have high numbers of PWSs relative to other states. For the three states with the highest number of health-based violations per PWS over this time period (Utah, Nebraska, and Missouri), only Missouri had a relatively high number of total violations.

While the state of Washington had the second highest number of health-based coliform violations immediately after the TCR was implemented (Fig. 4a), its number of violations decreased with time (fifth lowest number of violations in Fig. 4c) and performed the best of all states when violations were normalized by PWS (Fig. 5). Other states that performed well in terms of low numbers of violations per PWS include Illinois, New York, Tennessee, and Alabama (Fig. 5).

The geographic analysis could be expanded in future work by evaluating the impact of the implementation of the RTCR after additional time has passed. Data discussed above indicate that very small TNCWSs are disproportionately responsible for health-based coliform violations after the RTCR became effective (Table 2). Evaluating this finding for different geographic regions over a longer time period could help identify indicators that may be responsible for the high occurrence of violations for these PWSs. Furthermore, performing this geographic analysis at a greater resolution (*e.g.*, county level) would also be helpful to pinpoint such indicators.

Indicators that may have an impact on the occurrence of health-based microbiological drinking water quality violations may include age of the PWS, degree of urbanization,[17] income level,[17] source water quality, and weather/climate.[33,34] Such indicators could potentially be valuable as predictor variables for future modeling work as they are likely better predictors than geographic location at the resolution of the state level. It is tempting to consider whether predictive modeling could be used to determine the likelihood a PWS would incur a health-based violation of the RTCR to provide regulators and system operators with a tool to proactively intervene in the operation of a PWS and mitigate conditions that correspond to a high risk of causing a violation. Alternatively, PWSs at high risk of incurring health-based RTCR violations could be asked to perform additional assessments or monitoring, relative to PWSs at lower risk, to improve the likelihood of detecting water quality concerns. Since many of these PWSs likely are very small TNCWSs with limited resources, a more productive strategy could be to use predictive modeling to select PWSs that would benefit from technical assistance to improve their water quality. While such modeling efforts, to the best of our knowledge, have not been performed for microbiological drinking water quality violations, a recent study explored the possibility to use modeling as a risk assessment tool to predict which areas would be most at risk for nitrate violations.[35]

4. Conclusions

This study aimed to evaluate long-term trends of health-based drinking water quality violations experienced by PWSs in the conterminous U.S. Changes in drinking water regulations greatly impacted temporal trends in health-based drinking water violations. For most of the top nine contaminants/rules evaluated, the number of violations increased substantially soon after a new regulation became effective, then gradually decreased as PWSs addressed deficiencies causing these violations. The total number of health-based violations was especially influenced by the onset of the TCR in 1990 and the transition from the TCR to the RTCR in 2016. Health-based coliform violations were the most common type of health-based violation during the period the TCR was valid. The implementation of the RTCR caused a rapid decrease in the number of health-based coliform violations as expected by the U.S. EPA. An important change in the RTCR involved eliminating the requirement to report the detection of total coliforms as health-based violations. This TCR requirement was believed to be misleading as the detection of total coliforms is not an immediate public health concern. While a rapid decrease in the number of health-based coliform violations was observed once the RTCR became effective, it remains to be seen if the intended reduction in public health risk will materialize. Given the complexity of linking microbiological drinking water quality to drinking water-associated disease and outbreaks, it will be difficult to evaluate potential cause and effect relationships. The goal of including treatment technique violations in the RTCR was to provide incentives for improving microbiological water quality. One way to evaluate the potential health impact is to view trends of *E. coli* violations. Based on this metric, our analysis suggests that the implementation of the RTCR has not yet resulted in improved microbiological water quality, so continued evaluation of this and other measures will be important to assess the intended impact of the RTCR. Another way to evaluate public health risk is to study disparities among different PWSs. Our analysis indicates that very small PWSs and TNCWSs are disproportionately associated with health-based coliform and *E. coli* violations and that transition to the RTCR further exacerbated this trend for health-based coliform violations. If this trend persists over the next few years, providing greater resources and technical assistance to very small PWSs and TNCWSs seems to be an appropriate way to address these concerns.

Health-based coliform violations showed great geographic variability both when reporting total numbers of health-based coliform violations per state and total numbers of health-based coliform violations per state normalized by the number of PWSs. Expanding the geographic analysis by evaluating the impact of the implementation of the RTCR for different geographic regions, at a higher spatial resolution, and over a longer time period, could help identify factors responsible for the high occurrence of violations for very small PWSs and TNCWSs. Future work could use such factors as predictor variables for modeling work to provide regulators and system operators with a tool to select PWSs that would benefit from technical and financial assistance to improve their microbiological water quality.

Abbreviations and acronyms

CWS	Community water system
HAA5	Total haloacetic acids
MCL	Maximum contaminant level
NCWS	Non-community water system
PWS	Public water system
SDWA	Safe Drinking Water Act
SDWIS	Safe Drinking Water Information System NTNCWS – non-transient NCWS
TTHM	Trihalomethanes
TNCWS	Transient NCWS
U.S.	United States
U.S. EPA	U.S. Environmental Protection Agency

Conflicts of interest

There are no conflicts to declare.

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