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Cumulative risk analysis of carcinogenic contaminants in United States drinking water

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ABSTRACT

Cumulative risk analysis of contaminant occurrence in United States drinking water for the period of 2010–2017 indicates that over 100,000 lifetime cancer cases could be due to carcinogenic chemicals in tap water. The majority of this risk is due to the presence of arsenic, disinfection byproducts and radioactive contaminants. For different states within the U.S., cumulative cancer risk for drinking water contaminants ranges between 1×10^{-4} and 1×10^{-3}, similar to the range of cumulative cancer risks reported for air pollutants. Overall, national attributable risk due to tap water contaminants is approximately 4×10^{-4}, which is two orders of magnitude higher than the *de minimus* cancer risk of one-in-a-million. Thus, decreasing the levels of chemical contaminants in drinking water represents an important opportunity for protecting public health.

1. Introduction

Since the 1990s, researchers and health agencies worldwide have been calling for a shift towards aggregate and cumulative assessment of chemical contaminants from the prior framework that focused on assessing contaminants one at a time (European Commission Directorate-General for Health and Consumers, 2012; National Research Council, 1994; National Research Council, 2009; United States Environmental Protection Agency, 2003). Cumulative cancer- and non-cancer risk assessment has become a standard approach common for air quality evaluations conducted by the United States Environmental Protection Agency (2018a). Yet, no comprehensive cancer risk assessment has been published for drinking water contaminant occurrence on a national level, whether in the United States or any other country. Risk assessments have been typically conducted for individual drinking water contaminants such as arsenic or nitrate, or for small groups of related chemicals such as disinfection byproducts or metals. Here, we present the first application of the cumulative cancer risk framework to a drinking water dataset for the entire United States. Our approach builds on a recently published cumulative cancer risk assessment of water contaminants in the state of California (Stoiber et al., 2019) and offers a deeper insight into national drinking water quality.

2. Results & discussion

2.1. Lifetime cancer cases and cumulative cancer risk due to drinking water contaminants

This study utilizes a comprehensive nationwide dataset for contaminant occurrence in community water systems in the U.S., which our team compiled as a part of a multi-year research project, as described in prior publications (Schaider et al., 2019; Stoiber et al., 2019; Temkin et al., 2019). We analyzed water quality profiles for 48,363 community water systems. The dataset does not include water quality information for approximately 13.5 million American households, corresponding to approximately 14% of the U.S. population, that rely on private wells for their drinking water (U.S. Census, 2017; U.S. Geological Survey, 2014a).

Our cumulative risk assessment methodology follows the approach used in the National Air Toxics Assessment (U.S. Environmental Protection Agency, 2018a), whereby the overall cancer risk metric represents a statistical probability of developing cancer over a lifetime of exposure to an individual carcinogenic contaminant or a mixture of contaminants at specified levels. Risks of 10^{-6}, 10^{-5}, or 10^{-4} correspond to contaminant concentrations that, following a lifetime of exposure, would cause one cancer case in a population of one million, 100,000 or 10,000 people, respectively.

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In the U.S. EPA framework for air toxics assessment and in the present study, cancer risks for individual contaminants are treated additively, and cumulative risk is estimated by mathematical addition of single contaminant risks. This is a conservative approach which assumes that individual contaminants are exerting their toxic effects independently of each other, and that the mixture of contaminants is characterized by response additivity (U.S. Environmental Protection Agency, 2000). As summarized in extensive research and policy analyses, chemicals present in mixtures may act interactively, with cumulative effects that may differ from summed responses for individual chemicals (European Commission Directorate-General for Health and Consumers, 2012; U.S. Environmental Protection Agency, 2003). Some studies noted that chemical mixtures can show toxic effects exceeding those predicted from response additivity for single components (Cedergreen, 2014). Yet, in the absence of information on the interactions of water contaminants, response additive approach serves as a valuable first step towards cumulative risk assessment.

Here we included contaminants with cancer risk benchmarks established by an authoritative government agency such as the U.S. Environmental Protection Agency or the California Office of Environmental Health Hazard Assessment (Table 1). As described in detail in the U.S. EPA guidelines for carcinogen risk assessment, carcinogenic potency of different chemicals represents an upper bound estimate for cancer risk expected from a defined dose of substance per kilogram of body weight per day, following a lifetime of exposure to this dose of a contaminant (U.S. Environmental Protection Agency, 2005). For water contaminants, carcinogenic potency estimates can be translated into a benchmark concentration in water that corresponds to a risk of one cancer case per population of one million people, or 10^{-6} lifetime cancer risk. For chemicals included in this study, published cancer risk benchmarks are based on a linear dose-response model which assumes that any amount of exposure carries some risk.

The cancer risk calculations are based on the formulas described by Stoiber et al. (2019):

$$LCR = C_{LTA} / C_{RISK}$$

$$EC = \Sigma\,[LCR \times P_{CWS}], \text{ summed for all systems in a state or across the country}$$

$$EC_{TOT} = \Sigma\,[LCR \times P_{CWS}], \text{ summed for all contaminants}$$

$$CumR = EC_{TOT} / \Sigma\, P_{CWS}$$

Where:

LCR = lifetime cancer risk corresponding to a specified concentration of a contaminant

C_{LTA} = long-term average contaminant concentration in a community water system, calculated as an arithmetic average of all test results for the specified time period.

Table 1
Estimated lifetime cancer cases for drinking water contaminants in 48,363 community water systems in the United States.

Contaminant[1]	Drinking water concentration corresponding to 10^{-6} lifetime cancer risk[2]	Government agency defining 10^{-6} lifetime cancer risk level	Year published	Population exposed over 10^{-6} lifetime risk level, (millions)[3]	Estimated number of lifetime cancer cases[4]
Arsenic	0.004 μg/L	California OEHHA	2004	141	45,300
Hexavalent Chromium	0.02 μg/L	California OEHHA	2011	42	2,817
Disinfection Byproducts					
Bromodichloromethane[4]	0.06 μg/L	California OEHHA	2018 (proposed)	211	22,461
Chloroform[4]	0.4 μg/L	California OEHHA	2018 (proposed)	203	8,687
Dibromochloromethane[4]	0.1 μg/L	California OEHHA	2018 (proposed)	198	8,076
Trichloroacetic Acid	0.5 μg/L	U.S. EPA IRIS	2011	155	2,452
Dichloroacetic Acid	0.7 μg/L	U.S. EPA IRIS	2003	163	2,146
Bromoform[4]	0.5 μg/L	California OEHHA	2018 (proposed)	88	641
Bromate	0.1 μg/L	California OEHHA	2009	24	287
Radioactive Elements					
Radium-228	0.019 pCi/L	California OEHHA	2006	134	3,134
Radium-226	0.05 pCi/L	California OEHHA	2006	100	985
Uranium	0.43 pCi/L	California OEHHA	2001	57	336
Strontium-90	0.35 pCi/L	California OEHHA	2006	8	20
Tritium	400 pCi/L	California OEHHA	2006	0.2	7
Carcinogenic Volatile Organic Compounds (VOCs)					
1,2,3-Trichloropropane	0.0007 μg/L	California OEHHA	2009	11	290
Tetrachloroethylene	0.06 μg/L	California OEHHA	2001	13	91
1,2-Dibromo-3-chloropropane	0.0017 μg/L	California OEHHA	1999	4	63
1,4-Dioxane	0.35 μg/L	U.S. EPA IRIS	2013	5	23
Trichloroethylene	0.5 μg/L	U.S. EPA IRIS	2011	2	10
Carbon tetrachloride	0.1 μg/L	California OEHHA	2000	2	6
Vinyl chloride	0.05 μg/L	California OEHHA	2000	0.8	7
Benzene	0.15 μg/L	California OEHHA	2001	0.2	1

[1] Of 22 contaminants analyzed here, 17 have national drinking water standards in the U.S., either as individual chemicals (1,2-dibromo-3-chloropropane, arsenic, benzene, bromate, carbon tetrachloride, tetrachloroethylene, trichloroethylene, uranium, vinyl chloride) or as a group (dibromoacetic acid and trichloroacetic acid are regulated as a part of a group of 5 haloacetic acids, or HAA5; chloroform, bromoform, dibromochloromethane and bromodichloromethane are regulated as a group. Ra-226 and Ra-228 have a standard set for the sum of these two elements).

[2] Drinking water concentrations corresponding to 10^{-6} lifetime cancer risk were obtained from the websites of the California Office of Environmental Health Hazard Assessment (https://oehha.ca.gov/) and the U.S. Environmental Protection Agency Integrated Risk Information System (https://www.epa.gov/iris).

[3] For the exposure metric, arithmetic means for contaminant concentrations for each individual water utility were calculated for all available test results for a contaminant within the 2010 to 2017 data range. Test results reported as "non-detects" were assigned a value of zero and included in the overall data array.

[4] Estimated population exposed and estimated lifetime cancer cases for chloroform, bromoform, dibromochloromethane and bromodichloromethane are based on detection and concentration data for these individual contaminants. Estimates incorporating additional data for community water systems that measure and report the group of four trihalomethanes as a single total rather than individual trihalomethane levels are reported Table 3.

C_{RISK} = cancer risk benchmark that represents a contaminant concentration corresponding to 10^{-6} lifetime cancer risk
EC = estimated number of cases attributable to a contaminant
P_{CWS} = population served by a community water system
EC_{TOT} = estimated number of lifetime cancer cases due to multiple contaminants
CumR = cumulative lifetime cancer risk on a state or national level due to drinking water contaminants

We carried out an additional analysis for the group of four trihalomethanes (THM4), a cluster of four disinfection byproducts regulated in the United States as a single group with a legal limit of 80 μg/L. The THM4 group, defined by the U.S. EPA for regulatory purposes as "total trihalomethanes" or TTHM, includes chloroform, bromoform, dibromochloromethane and bromodichloromethane. While the majority of water systems in the United States monitor and report the levels of individual trihalomethanes in their water, approximately 9,359 water utilities in the United States only reported the combined THM4 concentration and not the levels of individual trihalomethanes for at least some years during the 2010–2017 period.

Therefore, to incorporate the data for community water systems that only reported combined THM4 levels and more accurately estimate the number of cancer cases due to the national occurrence of these contaminants, we followed a previously published approach for deriving a cancer risk benchmark for the THM4 group (California Office of Environmental Health Hazard Assessment, 2010). This approach combines 10^{-6} risk benchmarks for the individual trihalomethanes listed in Table 1 (California Office of Environmental Health Hazard Assessment, 2018) and factors in the national population-weighted average concentration for individual trihalomethanes to estimate their contribution to the overall THM4-attributable cancer risk, according to formulas below:

$$C_{RISK\ (group)} = \Sigma\ C_{PWA} / EC_{(group)}$$

$$C_{PWA} = \Sigma\ [C_{LTA} \times P_{CWS}] / \Sigma\ P_{CWS}$$

$$EC_{(group)} = \Sigma\ [C_{PWA} / C_{RISK}]$$

Where:

$C_{RISK\ (group)}$ = cancer risk benchmark representing a 10^{-6} lifetime cancer risk for the group of contaminants
C_{PWA} = population-weighted average concentration for a contaminant, summed for all water systems
$EC_{(group)}$ = estimated number of cancer cases attributable to a group of contaminants present at a defined concentration, such as the population-weighted average

The concentration-weighted 10^{-6} risk benchmark for the THM4 group corresponds to 0.15 μg/L and represents a benchmark that is lower than the 10^{-6} risk levels for chloroform and bromoform (0.4 and 0.5 μg/L, respectively), but higher than the 10^{-6} risk levels for dibromochloromethane and bromodichloromethane (0.1 and 0.06 μg/L, respectively). Applying this benchmark to the contaminant occurrence data for community water systems after including the additional THM4 data, we estimate that a further 8,047 lifetime cancer cases could be due to disinfection byproducts in the water, in addition to the estimates reported in Table 1.

Overall, tap water exposure to the carcinogenic contaminants analyzed in this study corresponds to 105,887 estimated lifetime cancer cases. For approximately 279 million people served by community water systems, or 86% of the U.S. population, this number of cases represents an overall cumulative lifetime risk of approximately 4×10^{-4}, equivalent to 4 lifetime cancer cases per 10,000 people. This risk level is two orders of magnitude greater than the one-in-a-million, or 10^{-6} risk benchmark that is often considered by regulatory agencies in the United States as the *de minimus* risk (Castorina and Woodruff, 2003). Estimated cancer cases due to disinfection byproducts and arsenic account for 87% of the total number of cases. The remaining cancer cases are due to radioactive chemicals in drinking water, hexavalent chromium, and carcinogenic Volatile Organic Compounds (VOCs).

It is important to highlight that the vast majority of the community water systems analyzed in this study were in compliance with U.S. national drinking water standards. For illustration, as the U.S. EPA data show, between 2014 and 2017, between 4.5-5.5% of community water systems had serious violations of national drinking water standards (U.S. Environmental Protection Agency, 2019). For 2017, the last data year included in this study, half of the 2,222 community water systems considered by the U.S. EPA to be a serious water quality violator were very small groundwater systems serving communities of less than 500 residents, and 86% of serious violations for 2017 were in water systems serving communities of less than 3,300 people (U.S. Environmental Protection Agency, 2019). However, as analysis in this paper shows, compliance with national drinking water standards does not mean that water contaminant levels are reduced to concentrations that, according to the latest research, are entirely without health risk. The majority of the cancer risk and estimated lifetime cancer cases correspond to community water systems that are in full compliance with drinking water standards.

Two considerations suggest that the present analysis is conservative and that the overall cumulative risk might be greater than what is reported here. First, contaminants included in this analysis are those for which robust national occurrence data are available. Numerous other contaminants, such as nitrosamines, unregulated disinfection byproducts, per- and polyfluoroalkyl substances (PFAS) and a variety of industrial and agricultural chemicals, are not monitored as frequently or are not monitored at all, precluding their inclusion in our study.

Further, even for nationally regulated water contaminants for which monitoring is required, not all utilities fully follow the monitoring and reporting regulations. For example, in 2017, of the over 50,000 community water systems in the U.S., 32 percent of systems had some non-compliance with monitoring and reporting requirements (U.S. Environmental Protection Agency, 2019). This lack of monitoring means some exposure information for water contaminants was either not collected or not reported to state and national drinking water authorities, and

Table 2
Cumulative lifetime cancer risks due to drinking water contaminants in community water systems in the United States.

Water system level lifetime cumulative cancer risk[1]	Surface water systems[2]		Groundwater systems[2]	
	Number of systems	Population exposed, millions of people	Number of systems	Population exposed, millions of people
More than 10^{-3}	326	9	4,029	8
10^{-4} to 10^{-3}	9,028	176	14,758	53
10^{-5} to 10^{-4}	851	9	11,890	22
Less than 10^{-5}	158	0.4	7,154	3

[1] For each risk tier, upper risk bounds are inclusive and lower risk bounds are exclusive.
[2] Only community water systems with reported information about population served were included in this analysis. Population statistics for community water systems were obtained from the U.S. EPA Envirofacts database (https://www3.epa.gov/enviro/facts/sdwis/search.html), and supplemented with data available from the United States Census and state drinking water programs, as described in Temkin et al. (2019). These population numbers are an estimate, and the specific number of customers and residents served by community water systems may differ.

therefore is not included in this study.

Second, this study also did not include noncarcinogenic contaminants that may increase the risk of cancer when present in combinations with other chemicals. The latest research suggests that noncarcinogenic chemicals might act together to promote the process of carcinogenesis (Miller et al., 2017). Thus, simultaneous presence of contaminants that are not recognized carcinogens may be relevant to cancer risk assessment and should be examined in future research.

2.2. Cumulative cancer risk analysis for groundwater and surface water systems

Water quality challenges faced by smaller, especially rural, communities have been well documented in the scientific literature (Allaire et al., 2018; Marcillo and Krometis, 2019) and regulatory analyses published by the U.S. EPA (2009, 2013). However, the present study demonstrates that water contaminants present in large communities contribute a significant share of overall cancer risk associated with drinking water, consistent with a recent report which noted that violations of health-based drinking water standards occur in community water systems of all sizes (Roberson, 2019).

According to the U.S. EPA statistics (2013), 71% of the population served by public water systems rely on surface water as the source of their drinking water. The rest of the population depends on groundwater systems, which are typically smaller than surface water systems. Overall, groundwater systems have the widest range of cumulative risk, from the lowest risk of 10^{-6} or less to the highest risk of greater than 10^{-3} (Table 2). The majority of surface water systems, all of which are required to treat water with disinfectants and thus have disinfection byproducts, typically present risk between 10^{-3} and 10^{-4}, although some surface water systems have risk significantly higher than 10^{-3}. Further, the surface water systems, due to the larger populations served, contribute a greater number of estimated cancer cases at every risk level.

As data in Table 2 demonstrate, there are many more groundwater systems compared to the number of surface water systems in the highest risk tier with cumulative risk greater than 10^{-3}. Water systems in the middle-risk tier, with cumulative lifetime cancer risk between 1×10^{-4} and 1×10^{-3}, serve a population of 229 million people for groundwater and surface water systems combined. Around 35 million people in the U.S. receive water with cumulative risk of 10^{-4} or lower (two lower risk tiers in Table 2). The distribution of risks for groundwater and surface water systems for arsenic and THM4 is represented visually in Fig. 1. We selected Arizona (Southwest), California (Pacific Coast), Illinois (Midwest) and New York (Northeast) as states representative of diverse geographies and distinct distributions of drinking water sources.

Cumulative cancer risk analysis for drinking water in all 50 U.S. states reflect greater water quality challenges faced by the states in the western part of the United States (Fig. 2). The western part of the United States is also the region that generally receives lower annual precipitation and has greater water scarcity. We analyzed the correlation between annual precipitation levels in each state of the United States, averaged over the study period of 2010–2017, and cumulative cancer risk due to drinking water contaminants in those states (Fig. 3). We observed a statistically significant correlation between these two parameters ($r^2 = 0.56$, $p < 0.001$). While many diverse factors influence water quality, from local geology and hydrology to land use and climate conditions, this correlation is compelling and illustrates a well-established connection between water quantity and quality (National Research Council, 2001). Drier conditions decrease water availability from surface water sources, concentrate contaminants in the existing water sources, and prompt communities to use groundwater resources even in areas where underlying aquifers may have higher levels of arsenic or radioactive chemicals. Thus, the observed correlation between annual precipitation and state-level cumulative cancer risk for drinking water contaminants is

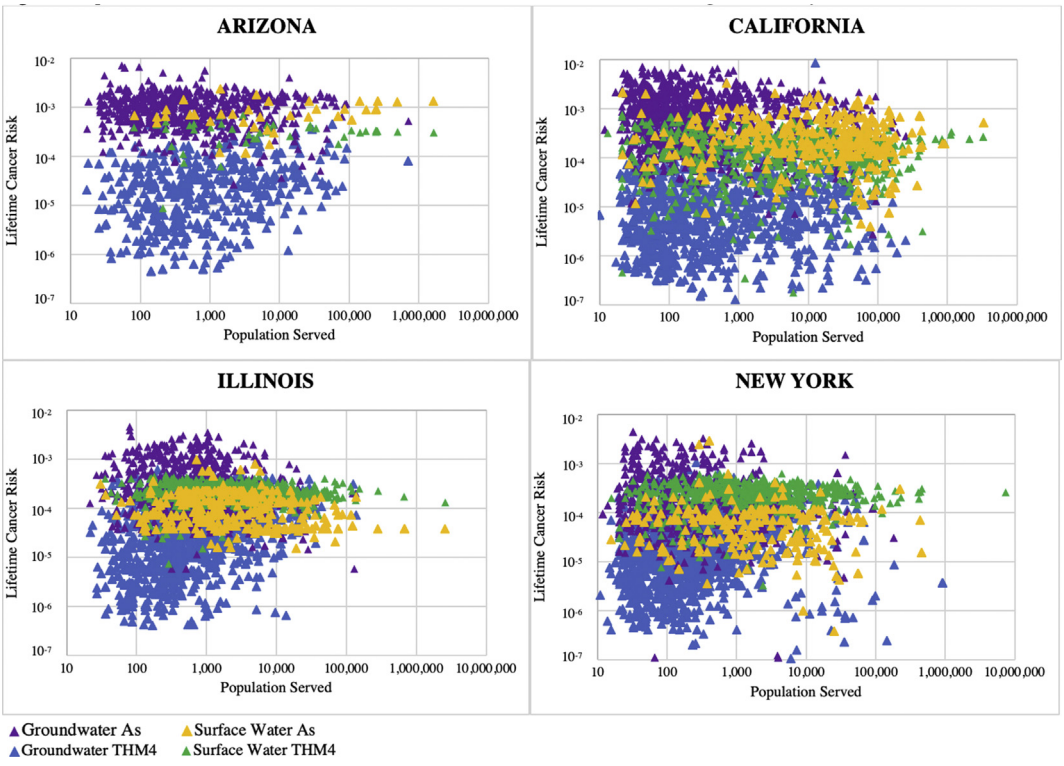

Fig. 1. Population-based distribution of arsenic and trihalomethane cancer risk for surface and groundwater systems in four states. Distribution of cancer risk due to the occurrence of arsenic and THM4 for surface and groundwater systems representing regional geographies within the United States: Arizona (Southwest), California (Pacific Coast), Illinois (Midwest) and New York (Northeast). X-axis: population served by each water system. Y-axis: lifetime cancer risk for each water system. Data shown here includes 2,026 systems serving 1.7 million people for THM4 and 3,777 systems serving 29 million people for arsenic. Community water systems in those states that did not detect or report THM4 or arsenic are not shown in the figure.

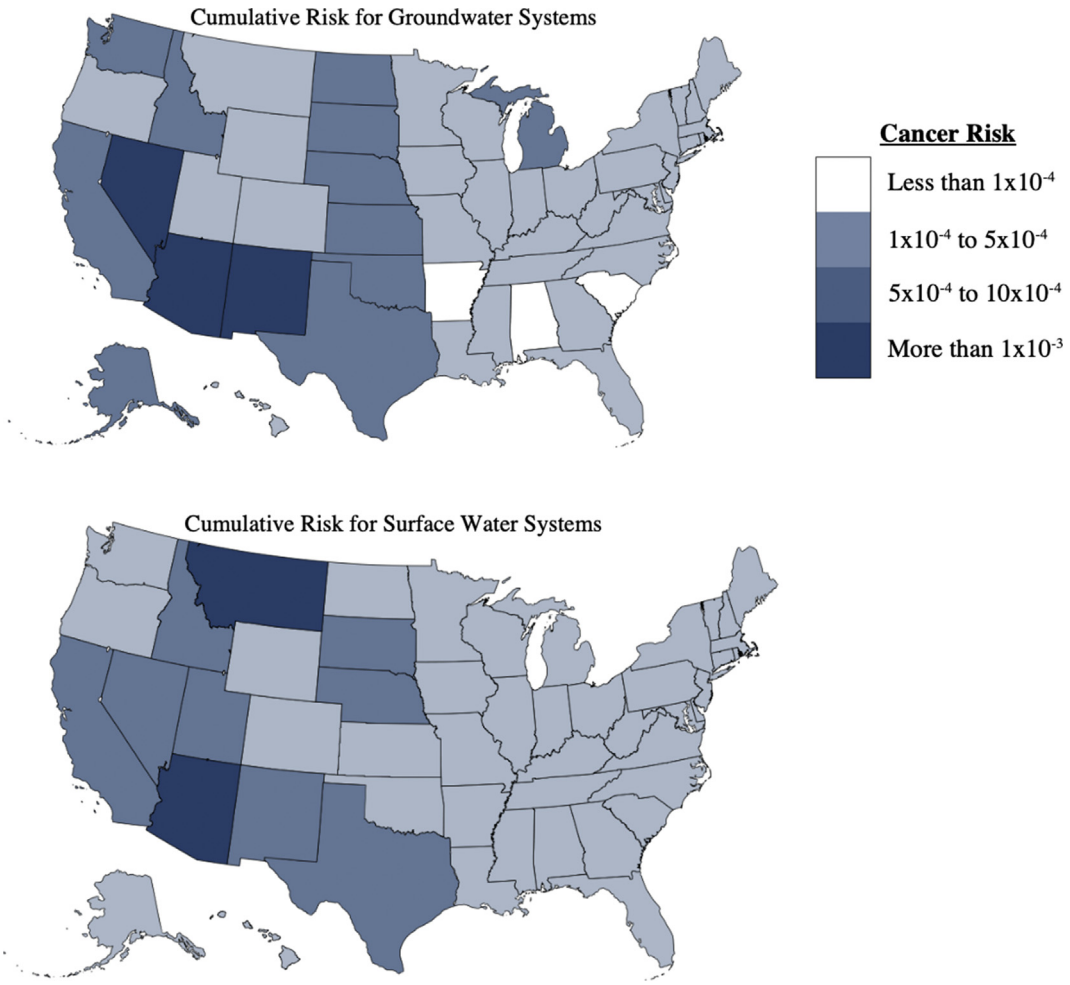

Fig. 2. State-level distribution of cumulative cancer risks due to drinking water contaminants. State-level distribution of cumulative cancer risks due to drinking water contaminants in surface and groundwater systems. Cumulative risk incorporates additional THM4 data reported as total trihalomethanes for community water systems for which individual THM4 concentrations were not reported. The full risk range is 1×10^{-4} to 17×10^{-4}.

consistent with information about the source water availability.

Further, contaminant occurrence in drinking water generally reflects the quality of the source water (Ascott et al., 2019). Across the U.S., arsenic is detected in 41 % of the wells sampled in aquifers used for drinking water at concentrations of 1 μg/L or more (United States Geological Survey, 2014b). Fig. 4 displays the variability of arsenic occurrence in drinking water in the U.S., with examples of states with high (Arizona in the Southwest), medium (New York in the Northeast),

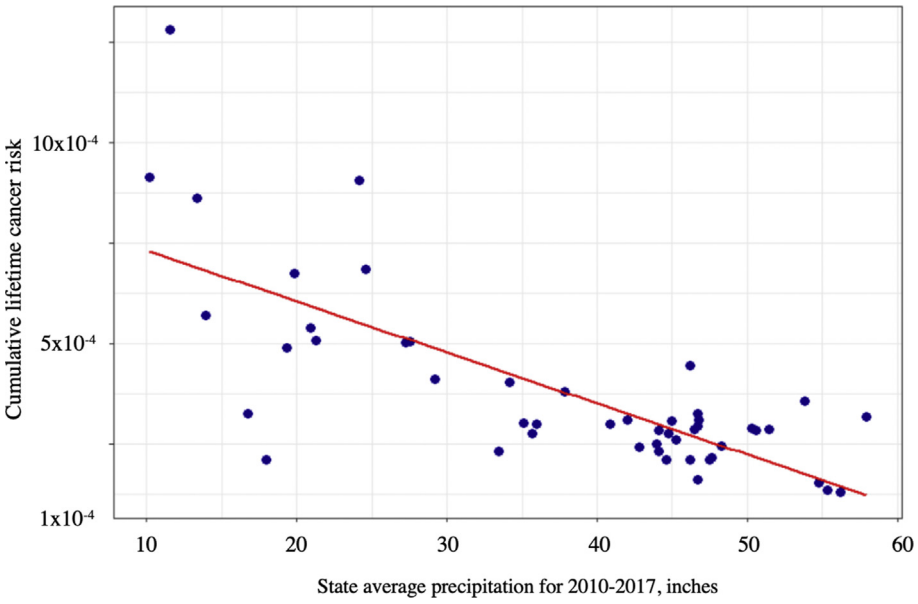

Fig. 3. Correlation analysis of state-level cumulative cancer risk and average rainfall. State-level precipitation is the arithmetic mean of annual state average precipitation reported by the National Oceanic and Atmospheric Administration statewide time series for 2010 to 2017, downloaded from https://www.ncdc.noaa.gov/cag/statewide/time-series. This data source has information for all states except Hawaii (not included in the figure). State-level cumulative lifetime cancer risk is reported in Table 3. The negative correlation ($r^2 = 0.56$) is statistically significant ($p < 0.001$).

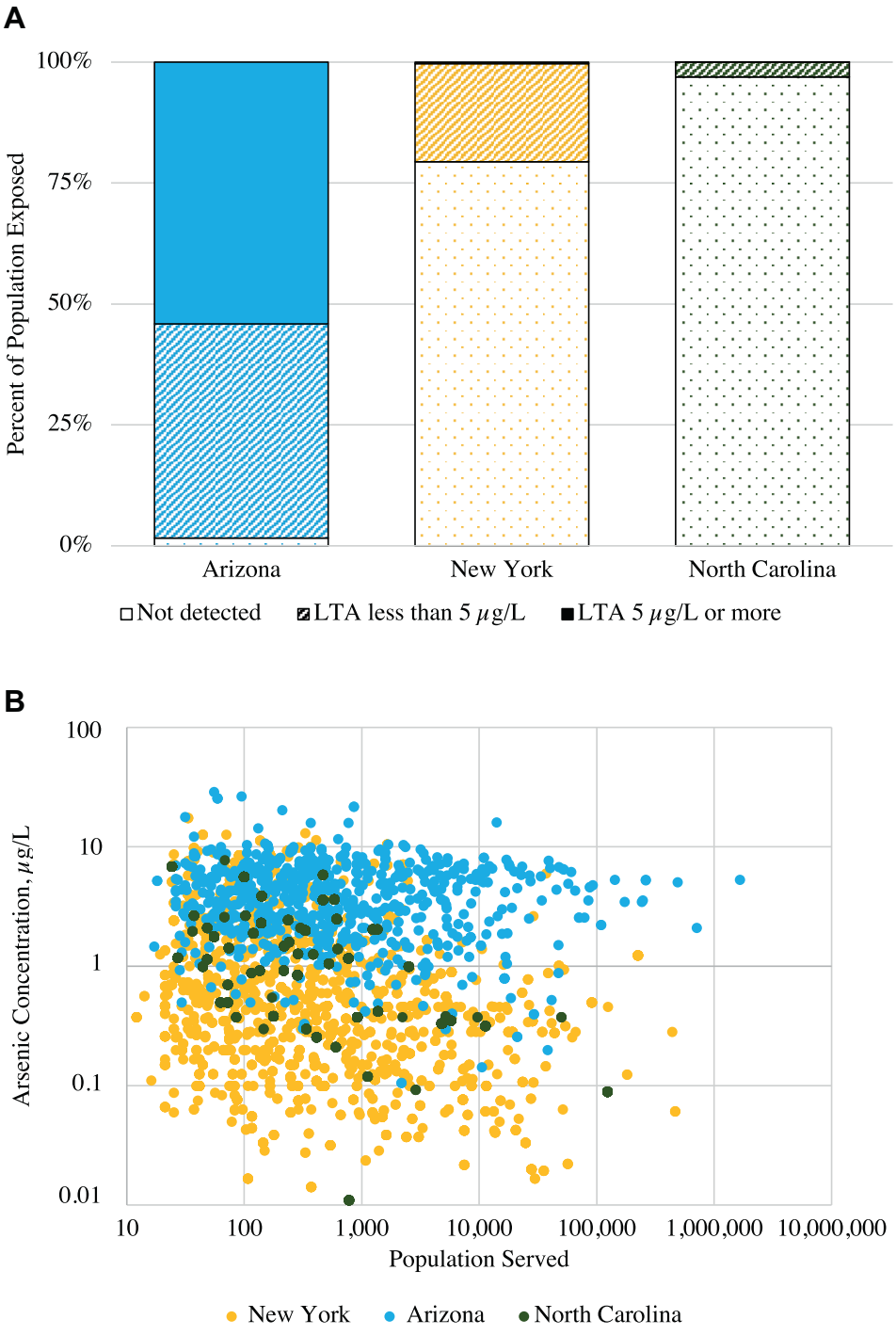

Fig. 4. Population exposed to arsenic and long term average (LTA) arsenic concentration per utility in three states. A: Proportion of the population served by community water systems exposed to drinking water with long term average (LTA) arsenic concentrations below the limit of detection/limit of reporting, detected up to 5 μg/L, and above 5 μg/L in three states, representing high (Arizona in the Southwest), medium (New York in the Northeast), and low (North Carolina in the South Atlantic) population-weighted arsenic concentrations. The long-term average concentration was calculated as arithmetic mean of all sample results for 2010–2017 for each utility. B: Population-based distribution of arsenic concentrations in community water systems in three states. X axis: population served by each water system. Y axis: average arsenic concentration for each system. With the X–Y scale presented in the figure, community systems with missing population data and systems with arsenic long-term average concentrations below 0.01 μg/L are not displayed. This corresponds to 98 systems serving 0.1 million people in Arizona, 1,937 systems serving 7.4 million people in North Carolina, and 1,527 systems serving 14 million people in New York.

and low (North Carolina in the South Atlantic) arsenic levels in drinking water. U.S. Geological Survey data show that both detections and concentrations of arsenic are generally higher in the western United States. Consistent with data on arsenic occurrence, population-weighted concentrations of arsenic are higher in drinking water systems in western U.S. states (Table 3), and groundwater systems have higher arsenic levels, as illustrated in Fig. 1.

In contrast to arsenic, which is typically a groundwater contaminant, higher levels of trihalomethanes and other disinfection byproducts are present in surface water systems, which, by law, must use disinfection to kill pathogenic microorganisms. Drinking water disinfection is essential and saves lives. Yet, high levels of organic matter in the source water result in elevated concentrations of disinfection byproducts which form when chlorine or other disinfectants react with organic materials. Drinking water treatment processes remove a part of the organic matter in source water, yet some remains, and these residual biological materials drive disinfection byproduct formation. Reports in the literature (AWWA Research Foundation, 2007; Kalankesh et al., 2019) and established water treatment practices (Ireland Environmental Protection Agency, 2012; United Kingdom Water Industry Research, 2000) demonstrate that THM4 concentrations in finished drinking water correlate with Total Organic Carbon (TOC) levels. In addition to total organic carbon levels, which reflect organic material contamination of source waters used as drinking water supplies, disinfection byproduct concentrations in

Table 3
State- and national-level average contaminant concentrations and cumulative lifetime cancer risks due to drinking water contaminants.

States, in alphabetical order	Cumulative cancer risk for population served by community water systems[1]	Population-weighted concentration of arsenic for community water systems, μg/L	Population-weighted THM4 concentration for community water systems, μg/L[1]
United States	4×10^{-4}	0.7	26
Alabama	1×10^{-4}	<0.1	17
Alaska	4×10^{-4}	0.9	18
Arizona	13×10^{-4}	4.2	31
Arkansas	3×10^{-4}	<0.1	36
California	5×10^{-4}	1.0	23
Colorado	2×10^{-4}	0.1	21
Connecticut	3×10^{-4}	0.1	32
Delaware	2×10^{-4}	0.1	18
Florida	4×10^{-4}	0.5	31
Georgia	2×10^{-4}	<0.1	29
Hawaii	1×10^{-4}	<0.1	4
Idaho	7×10^{-4}	2.4	8
Illinois	3×10^{-4}	0.3	26
Indiana	3×10^{-4}	0.3	23
Iowa	3×10^{-4}	0.3	27
Kansas	5×10^{-4}	1.1	28
Kentucky	3×10^{-4}	0.1	37
Louisiana	3×10^{-4}	0.6	22
Maine	3×10^{-4}	0.5	17
Maryland	2×10^{-4}	0.1	28
Massachusetts	2×10^{-4}	0.1	13
Michigan	3×10^{-4}	0.6	19
Minnesota	4×10^{-4}	1.0	16
Mississippi	1×10^{-4}	0.1	12
Missouri	2×10^{-4}	0.2	18
Montana	7×10^{-4}	2.0	20
Nebraska	9×10^{-4}	2.8	22
Nevada	9×10^{-4}	2.3	46
New Hampshire	2×10^{-4}	0.5	8
New Jersey	3×10^{-4}	0.3	29
New Mexico	9×10^{-4}	2.9	16
New York	3×10^{-4}	0.1	30
North Carolina	3×10^{-4}	<0.1	36
North Dakota	5×10^{-4}	1.3	22
Ohio	3×10^{-4}	0.1	35
Oklahoma	4×10^{-4}	0.5	35
Oregon	2×10^{-4}	0.4	21
Pennsylvania	3×10^{-4}	0.2	35
Rhode Island	3×10^{-4}	0.1	42
South Carolina	2×10^{-4}	<0.1	26
South Dakota	5×10^{-4}	1.5	24
Tennessee	2×10^{-4}	<0.1	18
Texas	5×10^{-4}	1.2	24
Utah	6×10^{-4}	1.7	11
Vermont	2×10^{-4}	0.1	19
Virginia	3×10^{-4}	<0.1	30
Washington	4×10^{-4}	1.2	18
West Virginia	3×10^{-4}	<0.1	34
Wisconsin	3×10^{-4}	0.6	11
Wyoming	3×10^{-4}	0.6	17

[1] Datasets used for the calculation of cumulative risk and trihalomethane concentrations incorporate data for community water systems that only report total THM4 concentration as a single metric as well as data for systems that reported the concentrations of individual trihalomethanes (chloroform, bromoform, bromodichloromethane, and dibromochloromethane).

finished water are also influenced by temperature, the presence of bromide, alkalinity/acidity of source waters, and the type of disinfectant (Huang et al., 2019; Ramavandi et al., 2015). Fig. 5 presents analysis of the total organic carbon and THM4 concentrations in treated water for 2,115 community water systems. As expected from prior studies, the correlation is statistically significant ($p < 0.001$).

2.3. Comparison of cumulative cancer risks for air and water contaminants

Air and water contaminants in the U.S. were regulated on roughly the same timescale, with the Clean Air Act in 1970 and the Safe Drinking Water Act in 1974. Cumulative risk assessment has now become a standard practice for air quality studies. Utilizing a cumulative approach for air quality data for 1990, a California-based study reported a median lifetime cancer risk due to air contaminants of approximately 3×10^{-4} (Morello-Frosch et al., 2000). Analyzing air quality data for the United States for the same year, Woodruff et al. (2000) reported a national risk of 2×10^{-4}. A subsequent study of nationwide air quality data for 1996 calculated the cumulative risk range between 6×10^{-4} and 10×10^{-4} (Loh et al., 2007). In contrast, a U.S. EPA National Air Toxics Assessment for 2014, the latest year data year available, reports a more modest risk of 3×10^{-5} which may be due to improved air quality across the country (United States Environmental Protection Agency, 2018b).

The risk ranges for carcinogenic drinking water contaminants reported in this study are similar to published estimates for cumulative cancer risks due to air contaminants. The range of drinking water contaminant-attributable cumulative cancer risks calculated here, 1×10^{-4} to 1×10^{-3}, reflects geographic differences and distinct water challenges that different states and communities face when working on providing safe drinking water for their residents. At a local scale, urban

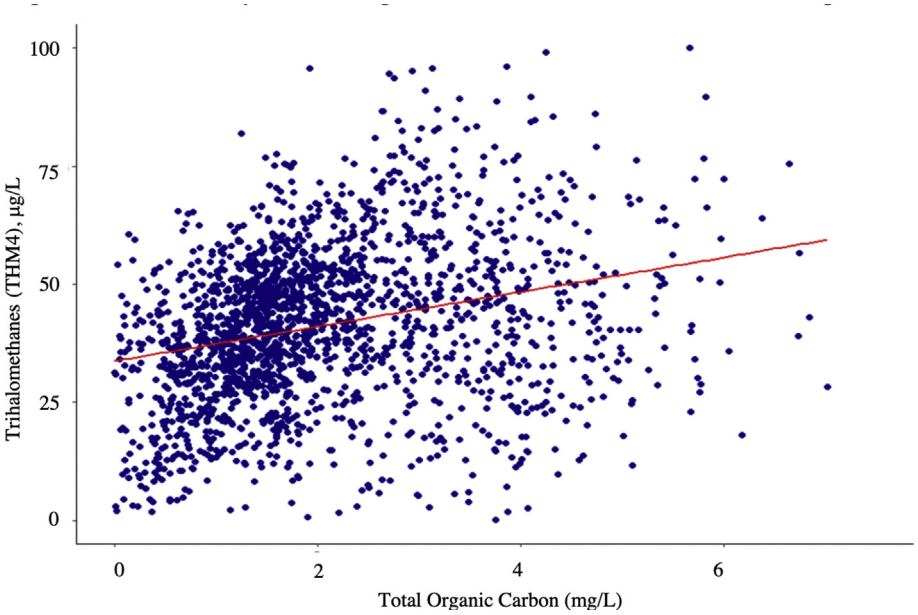

Fig. 5. Correlation analysis of Total Organic Carbon and THM4 concentration in drinking water. Correlation analysis for TOC and THM4 concentrations in treated water includes data for 2,115 community water systems for time period of 2012–2017. There is a weak but statistically significant positive correlation ($p < 0.001$) between the two parameters.

areas tend to face greater cumulative health risks from air pollution compared to non-urban areas, whereas the highest cancer risks associated with drinking water tend to occur in smaller communities.

As described by Loh et al. (2007), cumulative risk calculations for state- or national-level data are significantly affected by the unit risks assigned to individual carcinogenic contaminants. There are multiple examples whereby different agencies publish similar but not identical cancer risk benchmarks for the same contaminant. Additionally, as new research becomes available, the health benchmarks are re-evaluated and updated, which would also influence cumulative cancer risk estimates.

2.4. Data uncertainties and limitations

This study contains several data limitations and uncertainties. Our analysis includes reported data for contaminant occurrence in community water systems and does not include information on contaminants of private wells and their health risks. The study also does not include information for contaminants that are monitored infrequently by community water systems or not monitored at all. Our analysis is based on cancer unit risks published by government agencies for a subset of contaminants and does not incorporate information on contaminants for which health risk benchmarks are not available. It is important to recognize that cancer unit risks are based on an evolving body of science, and that future toxicological and epidemiological studies may indicate that carcinogenic potency of specific contaminants might be either higher or lower than currently available risk benchmarks summarized in this study.

As noted above, contaminant mixtures may exert their toxicological effects in ways that differ from the simple response additive framework used in the present study. If mixtures of carcinogenic contaminants in water were to elicit a synergistic, or "greater-than-additive" toxicity effect, the overall risk would be greater than estimated here with an additive model. Finally, this study does not account for the potentially heightened susceptibility of some subpopulations or age groups, and future research is needed to assess the possible health impacts of drinking water contaminant mixtures on infants and children.

3. Conclusions

This study is the first application of a cumulative cancer risk framework for a national-level analysis of drinking water contaminants for the entire United States. Overall, state- and national-level cumulative cancer risks due to carcinogenic water contaminants are similar in magnitude to the risks reported for carcinogenic air pollutants. Thus, improving water quality at the tap and investing in measures for source water protections represent opportunities for protecting public health and decreasing potential disease incidence due to environmental pollution.

Declarations

Author contribution statement

Sydney Evans: Conceived and designed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Chris Campbell: Contributed reagents, materials, analysis tools or data.

Olga V. Naidenko: Conceived and designed the experiments; Analyzed and interpreted the data; Wrote the paper.

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Competing interest statement

The authors declare no conflict of interest.

Additional information

The U.S. drinking water data analyzed in this study can be viewed through an open access web page at http://www.ewg.org/tapwater, and detailed information about the database is listed at https://www.ewg.org/tapwater/methodology.php.

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