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Radioactive Contaminants in U.S. Drinking Water and Water Quality Disparities

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Abstract

Radioactive contaminants, such as radium, radon, and uranium isotopes are naturally present in drinking water, and gas and oil extraction like hydraulic fracturing can exasperate radionuclide leakage into groundwater. The concentration of radionuclide in drinking water is dependent upon the water source and the underlying lithology within the aquifers. In United States, the Environmental Protection Agency regulates the level of radioactivity in drinking water via the gross alpha test, which is conducted to measure the emitted alpha particles as a result of the radioactive elements' natural decay. Radionuclides, such as radium and uranium, are known to cause bone cancer and other forms of cancer. Communities with crippling water purification infrastructure may be at a higher risk of being exposed to radionuclides, and this is a significant environmental justice concern. The radionuclide concentrations for the metropolitan or most populated city in each state in the United States and its territories (Puerto Rico, US Virgin Islands and Guam) were analyzed and correlated to the annual household income, to determine any disparities that maybe present. Lower income communities had elevated levels of radionuclides when compared to higher income communities which had lower frequency in elevated radionuclide contaminants.

Keywords

Radioactive Contaminants, Household Income, Income Per Capita, Environmental Justice, Water Quality, Radionuclides, Radium, Uranium, Radon, Cancer

1. Introduction

Radionuclides are intrinsically present in varying amounts in potable water. These radiological contaminants are released into the water source from rocks and bedrocks in the aquifers. The level of radionuclides is dependent upon the lithology of the underground structures (Agbalagba et al., 2012). Over time, erosion and dissolution increase the concentration of radiological elements that enter the water source (Ivanovich & Harmon, 1992). Uranium-234 (^{234}U) and Uranium-238 (^{238}U) are the most abundant radionuclides in the Earth's crust and consequently in potable water. In addition, radium-226 (^{226}Ra), radium-228 (^{228}Ra) and radon-222 (^{222}Rn) are environmental isotopes which are formed as result of radioactive decay of uranium and thorium present in rock and soil (Water Quality Association, 2020).

Radon and gross alpha radiation are released from the decay of various radioactive elements. Gross alpha can be present in drinking water because of the decay of uranium and thorium present in the Earth's crust (Ho et al., 2020). Although these radiations may not present any health risk outside the human body, ingesting them have been shown to be harmful, especially with long-term exposure (Ho et al., 2020).

Exposure to radiation can have various health risks depending on the source of radiation, the level of exposure (i.e. total dose), and the period of exposure (i.e. exposure length) (Ononugbo et al., 2013). The Environmental Protection Agency (EPA) enacted guidelines to mitigate the health risks associated with exposure to radionuclides, and consuming water near the federal drinking water standards (**Table 1**) puts consumers at low exposure levels. However, exposure of people to radionuclides through drinking water, when combined with other sources of exposure, can increase the likelihood of developing renal disease and cancer, such as radiation from medical treatments, living near coal mines and even traveling by airplanes (Avwiri et al., 2012). Considering the abundance of water and its necessity for everyday survival, the protection of water quality is an essential component of affective public health policy (WHO, 2017; IAEA, 2016).

To mitigate the health risks associated with exposure to radionuclides, the United States Environmental Protection Agency has regulated radium-226 (^{226}Ra) and radium-228 (^{228}Ra) to remain below 5 picocuries per litre of water (pCi/L), gross alpha including radium-226 to remain below 15 pCi/L, and uranium to remain below 30 μg/L, which has been converted by the EPA to be approximately 20 pCi/L (EPA, 2001).

Many of the drinking water standards were put in place decades ago and have not been updated. The Environmental Working Group (EWG) collaborates with state and federal agencies to obtain tap water quality data and provides health

Table 1. EPA maximum contaminant levels (MCLs) for radionuclides in drinking water (excluding radon).

Contaminant	MCL
Combined radium-226 and radium-228	5 pCi/L
Gross alpha including Ra-226	15 pCi/L
Uranium	30 μg/L or 20 pCi/L

guidelines, which may not be taken into consideration at a federal level. EWG regulations consider the heightened vulnerability of chemical toxicity to children, immunocompromised individuals, and pregnant women, to bridge the gap between the outdated federal standards (EWG, 2019; Environmental Protection Division, 2020). Hence, although many drinking water facilities are within legal compliance for toxic chemicals mandated by the federal agencies, these regulations are not always safe. These toxic chemicals and new emerging chemicals leave the general population susceptible to health problems. The Environmental Protection Agency sets the legal limits for combined radium (−226 & −228) while the EWG health guidelines limit radium levels at 0.05 pCi/L (EWG, 2019). In addition to discrepancies between the health guidelines and federally mandated guidelines, social disparities are also an undeniable problem facing drinking water treatment facilities, as shown in a study correlating race/ethnicity and socioeconomic backgrounds to arsenic and nitrate levels (Balazs et al., 2011; Balazs et al., 2012). Previous studies have demonstrated water quality disparities correlating to socioeconomic background to demonstrate chemical, biological and physiccal contaminant levels (Karim et al., 2020), but this study is the first of its kind to elaborate on the correlation and association between radioactive contaminant levels in drinking water and socioeconomic background.

Radionuclides may be removed from drinking water source via reverse osmosis and ion exchange technology to increase drinking water quality (EPA, 2015). However, communities with crippling water purification infrastructure and lower income communities may be at a higher risk of being exposed to radionuclides, which is a significant environmental justice concern (Karim et al., 2020). To understand the social disparities, it is important to conduct a quantitative analysis in order to examine whether vulnerable populations, especially those with lower-average household incomes, are disproportionately impacted by radionuclides contaminants in drinking water. This research aims to analyze the possible disparities in drinking water quality in the metropolitan cities of each state in the United States and the US territories, including Puerto Rico, Guam, and the US Virgin Islands.

2. Materials and Methods

Secondary data related to the concentrations of radioactive contaminants was obtained from the annual water safety report for the metropolitan areas across the United States for 2019 and the details are provided in the following table (**Table 2**).

Additional information was collected by contacting water service offices to obtain information not readily available in the annual consumer confidence report (CCR). Data including median annual household income was obtained from the United States Census Bureau (United States Census Bureau, 2020). The water quality data was then prepared for descriptive statistical analysis. Histograms were used to illustrate the levels of total radionuclide in metropolitan

Table 2. Radionuclide resource list for each state.

State	Drinking Water	State	Drinking Water
Alabama	Alabama Water Quality Report, 2019	Montana	Montana Water Quality Report, 2019
Alaska	Alaska Water Quality Report, 2019	Nebraska	Nebraska Water Quality Report, 2019
Arizona	Arizona Water Quality Report, 2019	Nevada	Nevada Water Quality Report, 2019
Arkansas	Arkansas Water Quality Report, 2019	New Hampshire	New Hampshire Water Quality Report, 2018
California	California Water Quality Report, 2018	New Jersey	New Jersey Water Quality Report, 2019
Colorado	Colorado Water Quality Report, 2019	New Mexico	New Mexico Water Quality Report, 2019
Connecticut	Connecticut Water Quality Report, 2018	New York	New York Water Quality Report, 2018
Delaware	Delaware Water Quality Report, 2019	North Carolina	North Carolina Water Quality Report, 2019
Florida	Florida Water Quality Report, 2019	North Dakota	North Dakota Water Quality Report, 2019
Georgia	Georgia Water Quality Report, 2019	Ohio	Ohio Water Quality Report, 2019
Hawaii	Hawaii Water Quality Report, 2019	Oklahoma	Oklahoma Water Quality Report, 2019
Idaho	Idaho Water Quality Report, 2019	Oregon	Oregon Water Quality Report, 2019
Illinois	Illinois Water Quality Report, 2019	Pennsylvania	Pennsylvania Water Quality Report, 2019
Indiana	Indiana Water Quality Report, 2019	Rhode Island	Rhode Island Water Quality Report, 2019
Iowa	Iowa Water Quality Report, 2019	South Carolina	South Carolina Water Quality Report, 2019
Kansas	Kansas Water Quality Report, 2019	South Dakota	South Dakota Water Quality Report, 2018
Kentucky	Kentucky Water Quality Report, 2019	Tennessee	Tennessee Water Quality Report, 2019
Louisiana	Louisiana Water Quality Report, 2019	Texas	Texas Water Quality Report, 2019
Maine	Maine Water Quality Report, 2019	Utah	Utah Water Quality Report, 2019
Maryland	Maryland Water Quality Report, 2019	Vermont	Vermont Water Quality Report, 2019
Massachusetts	Massachusetts Water Quality Report, 2019	Virginia	Virginia Water Quality Report, 2019
Michigan	Michigan Water Quality Report, 2018	Washington	Washington Water Quality Report, 2019

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Minnesota	Minnesota Water Quality Report, 2018	**West Virginia**	West Virginia Water Quality Report, 2019
Mississippi	Mississippi Water Quality Report, 2018	**Wisconsin**	Wisconsin Water Quality Report, 2018
Missouri	Missouri Water Quality Report, 2019	**Wyoming**	Wyoming Water Quality Report, 2019
Guam	Guam Water Quality Report, 2019	**Puerto Rico**	Puerto Rico Water Quality Report, 2019
US Virgin Islands	Zack et al., 2020		

areas across the United States, Puerto Rico, US Virgin Islands and Guam for 2019. Tables were generated to record income per capita for the metropolitan city of each state and US territories (provided by the Census Bureau) and their drinking water source (provided by the state and local water services departments), and correlated to the levels of total radionuclide concentrations. The disparities among the average household income in different counties and their water quality are shown using multi-variable charts.

3. Results and Discussion

The correlation between the average household income radionuclide levels is examined to determine the impact of median household income on the quality of drinking water. The drinking water sources in each state are different; however, most of the water sources are either from surface water or groundwater, as shown in **Table 3**. Raw water chemistry and composition can be influenced by many factors including human activity and wildlife population surrounding the water source, but rock formation is particularly responsible for level of radionuclides present in drinking water due to the decay of uranium from Earth's crust. Radium, radon, and uranium isotopes are an intrinsic part of water, but these radionuclide levels are exasperated due gas and oil extraction like hydraulic fracturing which can leak into groundwater (USGS, 2020). Hence, the concentration of radionuclide in drinking water is dependent upon the water source (**Table 3**) and the underlying lithology within the aquifers.

In the United States, the Environmental Protection Agency regulates the level of radioactivity in drinking water via the gross alpha test, which is conducted to measure the emitted alpha particles due to the radioactive elements' natural decay. The details and regulatory limits are indicated in **Table 1**, and were put into place decades ago. Research has shown that health agencies recommend radionuclides in drinking water to be significantly lower than the federal mandates.

The radionuclide concentrations for the metropolitan or most populated city in each state in the United States, Puerto Rico, Guam, and US Virgin Islands were analyzed and correlated to the annual household income (**Table 4**) to determine disparities that maybe present, as shown in **Figure 1**.

Table 3. Drinking water source in the metropolitan city of each state in the United States.

State	Drinking Water Source	State	Drinking Water Source
Alabama	Potomac River	Montana	Missouri River
Alaska	Eklutna Lake	Nebraska	Platte River
Arizona	Salt and Verde Rivers	Nevada	Kings Creek, Ash Creek and Marlette
Arkansas	Lake Winona and lake Maumelle	New Hampshire	Bellamy Reservoir
California	Sacramento and American River	New Jersey	Pequannock Watershed
Colorado	Strontia Springs	New Mexico	Bernalillo Rivers and Creeks
Connecticut	Farmington River	New York	Catskill/Delaware and Croton
Delaware	Heron Bay	North Carolina	Falls Lake Reservoir
Florida	Floridan Aquifer	North Dakota	Red River
Georgia	Chattahoochee River	Ohio	Scioto River
Hawaii	Haiku Tunnel and Well	Oklahoma	Canton Lake and McGee Creek
Idaho	Boise River	Oregon	Clear Creek
Illinois	Lake Springfield	Pennsylvania	Schuylkill River
Indiana	White River	Rhode Island	Scituate Reservoir
Iowa	Raccoon and Des Moines River	South Carolina	Lake Keowee
Kansas	Kansas River	South Dakota	Hilger's and Whiskey Gulch basin
Kentucky	Old Hickory Lake	Tennessee	Cumberland River
Louisiana	Southern Hills Aquifer	Texas	Lake Austin
Maine	China Lake	Utah	Cottonwood Creek
Maryland	Magothy River, Upper and Lower Patapsco	Vermont	Berlin Pond
Massachusetts	Ware River	Virginia	James River
Michigan	Saginaw Sandstone Aquifer	Washington	Cedar River
Minnesota	Mississippi River	West Virginia	Elk River
Mississippi	Pearl River	Wisconsin	Lake Michigan
Missouri	Missouri River	Wyoming	Granite Springs Reservoir
Guam	Northern Guam Lens Aquifer	Puerto Rico	Karst Aquifer
US Virgin Islands	Seawater		

To investigate disparities in drinking water quality, total radionuclides were examined, including combined radium (5 pCi/L), uranium (20 pCi/L) and gross alpha (15 pCi/L) for a total of 40 pCi/L. Many states failed to document uranium and gross alpha levels. However, most of the states and the US territories

Table 4. Median household income along with income per capita (US dollars) for metropolitan city of each state in the United States, Puerto Rico, Guam, and US Virgin Islands. The incomes are separated by a slash (/).

State	Median household income/income per capita ($)	State	Median household income/income per capita ($)
Alabama	38,902/24,780	Montana	57,172/33,107
Alaska	83,648/30,129	Nebraska	59,266/21,265
Arizona	57,957/21,907	Nevada	53,575/26,011
Arkansas	53,173/34,546	New Hampshire	73,022/29,296
California	62,474/29,906	New Jersey	72,561/19,313
Colorado	68,377/32,399	New Mexico	51,643/24,745
Connecticut	73,151/34,310	New York	67,274/35,811
Delaware	69,479/29,007	North Carolina	60,764/24,698
Florida	41,818/25,601	North Dakota	53,309/26,059
Georgia	65,345/25,288	Ohio	52,971/23,020
Guam	61,937/16,549	Oklahoma	53,973/25,074
Hawaii	80,212/36,339	Oregon	73,097/31,377
Idaho	63,179/25,723	Pennsylvania	46,116/22,874
Illinois	57,238/23,074	Puerto Rico	20,296/12,081
Indiana	47,678/23,198	Rhode Island	42,158/25,435
Iowa	47,275/23,316	South Carolina	63,459/28,649
Kansas	46,890/23,326	South Dakota	50,017/26,959
Kentucky	57,405/21,756	Tennessee	55,873/23,994
Louisiana	57,843/27,934	Texas	52,210/24,516
Maine	56,977/24,132	Utah	73,730/24,277
Maryland	85,203/29,771	Vermont	50,324/31,095
Massachusetts	71,834/37,311	Virginia	111,574/33,671
Michigan	31,283/21,701	Washington	70,598/39,322
Minnesota	63,590/35,388	West Virginia	41,701/27,138
Mississippi	55,700/26,655	Wisconsin	70,463/25,163
Missouri	43,889/22,698	Wyoming	63,235/29,980
US Virgin Islands	37,254/21,362		

reported the combined radium levels. US Virgin Islands did not report any radionuclide levels. The data obtained for Puerto Rico was from a report conducted in 2017 showing that Puerto Rico had five violations for elevated radionuclide levels (NRDC, 2017). However, considering that radionuclides do not decay from the environment as quickly, these results are still valid, indicating that Puerto Rican drinking water does not meet federal regulations. As shown in **Figure 1**, as the income increases, radionuclides contaminants become less

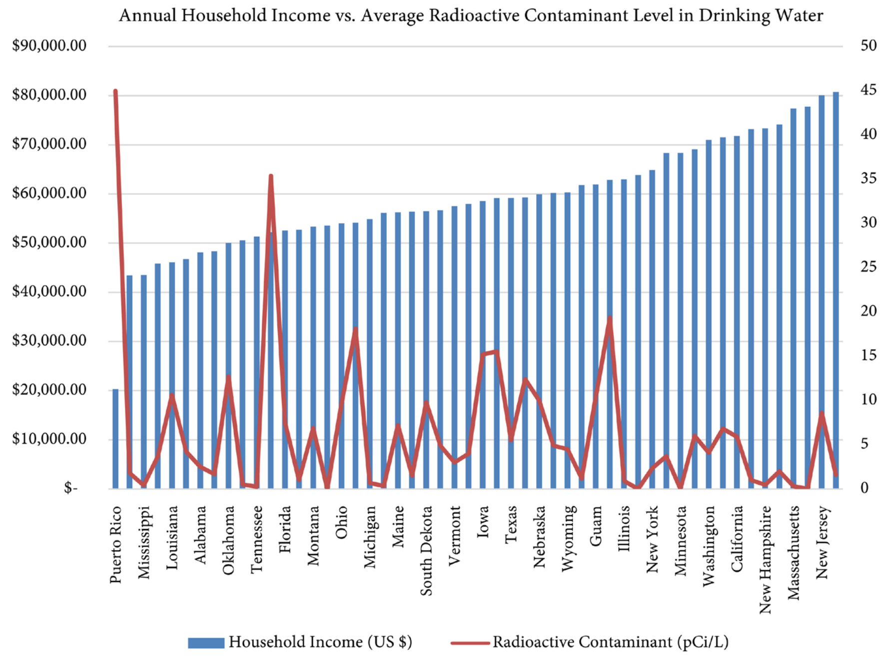

Figure 1. Average radiological contaminant present in drinking water as it correlates to income per capita in the metropolitan city of each state. Data for Missouri, Hawaii, and Minnesota was not readily available, as these states do not report on radionuclides. Data for Puerto Rico was obtained from a previous study conducted in 2017, where there were five violations for radionuclides in drinking water (NRDC, 2017).

frequent in drinking water. Indiana, Idaho, Iowa, Delaware and Pennsylvania had the highest levels of radionuclides. These state's incomes fall in the lower- and middle-class brackets. However, states with higher incomes did not have high levels of radionuclides in their drinking water.

Upon closer examination, Idaho's combined radium, uranium and gross alpha levels were 2.3, 18, and 6.1 pCi/L respectively, for a total of 35.4 pCi/L out of 40 pCi/L as mandated by the EPA. Indiana's combined radium, uranium and gross alpha levels were 1.73, 9.7, and 6.7 pCi/L, respectively. Iowa's combined radium, uranium and gross alpha levels were 2.2, 1.9, and 11.1 pCi/L, respectively. Pennsylvania's combined radium, and gross alpha levels were 3.95 and 11.6, respectively. Finally, Delaware's uranium and gross alpha levels were 12.78 and 6.6 pCi/L, respectively. Furthermore, Guam also had moderately elevated levels of radionuclides. Data for Missouri, Hawaii and Minnesota was not readily available, as these states did not report the levels of radionuclides. The general trend within the graph in **Figure 1** indicates elevated radionuclide levels among low- and middle-income brackets, but significantly lower radionuclide among higher income states.

Although there were violations in Puerto Rico, the US states remained well below the federally mandated regulations for radionuclides in drinking water. However, these regulations were set two decades ago, and according to the Environmental Working Group (EWG), are not low enough to mitigate health issues that might arise due to exposure to radionuclides. According to the EWG health guidelines, radium levels should remain 0.05 pCi/L compared to the 5 pCi/L, which is 100 times more than the health guideline recommendations. In addition, the EPA standard for uranium is at about 20 pCi/L which is 46.5 times higher than the EWG health guidelines of 0.43 pCi/L. Tennessee ranks among the lowest for combined radium at 0.26 pCi/L, which is 5.2 times the EWG health guideline limits and significantly lower than the national average of 0.47 pCi/L (EWG, 2019).

Finally, the general trend in **Figure 1** shows that low- and middle-income communities had higher radionuclides in drinking water compared to high income communities. Although, there was one incident where Delaware had a slightly more elevated radioactive contaminant level within the high-income bracket group, perhaps this is due to an outlier in the compiled data. However, the general scheme and pattern indicate that there is much more frequency in the elevated radionuclide contmiant levels among low- and middle-income bracket groups. These disparities in radionuclide levels in correlation to income levels are in conjunction with water justice inequalities that have been previously investigated by scientists and environmentalists. Our findings that lower income communities face injustice obtaining and sustaining high water quality agree with previous investigations (Karim et al., 2020). In addition, federally mandated regulations should be reviewed to better mitigate health problems that could arise from drinking contaminated water.

4. Conclusion

Water resource management is a global concern and protecting the quality of drinking water is a public health duty. Due to the carcinogenic effects of radionuclides, the presence of these contaminants in drinking water at a disproportionate level in lower income communities is dire and of social and epidemiological interest. As shown in this study, in 2019, Indiana, Idaho, Iowa, Delaware and Pennsylvania with median household incomes in the low- to mid-income communities demonstrated high levels of radionuclides. In contrast, communities with high incomes had significantly lower levels of radionuclides in their drinking water. In addition, Puerto Rico, a US territory where water quality must meet US EPA standards has five violations for elevated levels of radionuclides in drinking water. In addition, Guam's drinking water was also slightly higher than many US states. Finally, although all the US states met the EPA's legal standards, which were put in place two decades ago and are highly outdated. According to the EWG's health guidelines, the standards for radionuclides are significantly lower than federal mandates.

Man-made and naturally occurring factors play a significant role in the quality and composition of water. However, public water quality should not be influenced by socioeconomic factors. Based on the results from data obtained across the United States, poor water quality is much more frequent in less affluent communities, due to the presence of industrial activity, human activity, and is exasperated by an already collapsing water infrastructure.

Based on this study, it is recommended for water infrastructures to be improved by incorporating newer technology to reduce radionuclides from drinking water, as they pose health risks. In addition, federal regulations must be improved and restrictions adequately imposed for radioactive material. Finally, states that do not report on radionuclides must be held accountable for not making this information readily available and accessible to consumers. Information obtained from the present study could also be used to draft improved health guidelines, and for the purpose of resource allocation to ensure that the general population is better informed about drinking water quality within their communities.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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