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Drinking Water Disparities in Tennessee: The Origins and Effects of Toxic Heavy Metals

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Abstract

Several toxic metals, commonly present in drinking water, are believed to play important roles in the development of cancerous tumors. Although the US Safe Drinking Water Act requires drinking water to meet health standards set by the Environmental Protection Agency, violations occur regularly. In this study, we have investigated the role of the two predominant toxic heavy metals identified in the drinking water sources in Tennessee: copper and lead. We have analyzed the levels of copper and lead, as well as the total water hardness among different counties of Tennessee, with different socioeconomic backgrounds. We determined that the effects of lead and copper in drinking water were random, although counties with typically lower average household incomes typically had higher levels of the metals. The contaminant levels were found to remain below the threshold established by the Environmental Protection Agency and the State of Tennessee. Water from the Cumberland River was harder than water obtained from other rivers in Tennessee. Furthermore, the total hardness of water did not correlate with the average household income of the various counties.

Keywords

Drinking Water, Water Safety, Environmental Justice, Water Contaminants, Toxic Metals, Copper, Lead

1. Introduction

Water sustains life and is essential for a healthy ecosystem, agriculture, as well as for industrial and economic growth. Clean water is essential to the health and well-being of the general populace, worldwide. The World Health Organization (WHO) estimates that approximately eight hundred million people still do not have access to basic drinking, clean, or advanced water sources (World Health

Organization, 2019). It is also estimated that approximately two billion people utilize drinking water contaminated with fecal matter. As the population continues to grow, obtaining and sustaining water quality has become a growing challenge. Water quality is compromised by many factors such as human wastes and toxic chemicals from industrial wastes, radiological wastes, and infectious agents. In fact, infectious agents are the primary contaminants responsible for more than eight hundred thousand deaths every year, globally.

The United States Environmental Protection Agency (EPA) is responsible for regulating water safety and updating the Contaminant Candidate List (CCL), which includes chemical contaminants such as copper, lead, 1-butanol, 1,3-butadiene, 3-hydroxycarbofuran, acetochlor, and aniline, as well as microbial contaminates such as E-coli, Enterovirus, Hepatitis A, Salmonella, and Naegleria Fowleri (United States Environmental Protection Agency, 2018). In 1974, the Safe Drinking Water Act (SDWA) was passed by US Congress (United States Environmental Protection Agency, 1974), which obligates the EPA to implement standards for public drinking water. The EPA considers copper, lead, as well as certain microorganisms as some of the major contaminants, and there are laws in place to regulate the amount of these contaminants in city water systems. In this study we investigated the levels of copper and lead in the drinking water of various counties in Tennessee, as well as the total hardness of water as compared to the average household income in the different counties.

1.1. Water Safety in Tennessee

Drinking water in Tennessee can be obtained from city water systems and from private underground water sources, such as wells. Consumable water can also be obtained from springs, lakes and rivers, as shown in **Table 1**. The Tennessee Department of Environment and Conservation's Division of Water Resources enforces regulations to ensure that the drinking water in Tennessee is safe for human consumption. The Division of Water Resources tests drinking water for microbial pathogens that may cause infection among the general populace. In addition, chemical, biohazard and disinfectant level are regularly inspected (TN Department of Health, 2019).

The laws and regulations surrounding water safety have been established since the formulation of the EPA by former President Richard Nixon. In addition, the State of Tennessee has numerous statutes regulating water quality, such as Safe Dams Act, Tennessee Safe Drinking Water Act, Water Withdrawal Registration Act, Water Wells Act, Water Quality Control Act. The Safe Dams Act is in place to legislate the construction of dams that are not federally funded or initiated (TN Department of Environment and Conservation, 2019). This is important for the flow of water and the duration that water remains in the dam. In addition, the construction material is thoroughly inspected to ensure that it does not contaminate the water system.

Regulatory measures can easily be implemented in city water systems. However, it is estimated that 95% of the rural residents consume water from private

Table 1. Water sources in Tennessee counties.

County	Water Source
Anderson	Clear Creek Spring
Carter	Hampton Spring, Valley Forge Spring, and Big Spring
Cumberland	Holiday Hills Lake
Davidson	Cumberland River
DeKalb	Smithville City Reservoir
Dyer	Memphis Sand Aquifer
Hamilton	Tennessee River
Knox	Tennessee River
Madison	Cumberland River
Maury	Duck River
Montgomery	Cumberland River
Putnam	Center Hill Lake
Rutherford	Stones River and J. Percy Priest Lake
Shelby	Memphis Sand Aquifer
Sullivan	South Fork Holston River
Sumner	Old Hickory Lake
Washington	Watauga River and Unicoi Springs
Williamson	Cumberland River

sources, such as wells (TN Department of Health, 2019), which can make regulatory measures harder to implement. Water in Tennessee is typically regulated for two major contaminants (copper and lead) as these metals can have significant effect on the health and well-being of individuals.

Tennessee, like other places, uses the same water purification techniques to ensure that the public drinking water is free of contaminants. The water treatment process typically includes some form of pre-chlorination or aeration to limit the growth of microorganisms and algae. Following the pre-chlorination process, coagulation is performed to remove any reactive chemicals that might be present in the water source. In addition to coagulation, slow-sand filtration may also be utilized to remove reactive chemicals from the water source. Typically, only one system of coagulation is chosen, based on the type of reactive chemicals that might be present in the water source. Following the reactive chemical removal, sedimentation is used to eliminate any suspended solids that might have been trapped in the resin during the coagulation process. Finally, the water is ready for filtration using different types of systems, such as reverse osmosis, ultra-filtration, distillation, and ion exchange (United States Environmental Protection Agency: Office of Wastewater Management, 2004; Burton & Stensel, 2003).

1.2. Primary Water Contaminants and Purification Techniques

1.2.1. Copper

Copper is an essential dietary mineral for all organisms, especially human beings. The most important role of copper has been its use in piping to carry water to private households. Due to its malleability, copper has become the main component for electrical wiring and household plumbing. Copper can enter drinking water due to mining, as pesticide runoff from farming, and from industrial and manufacturing waste leakage into lakes and rivers. City water can have higher copper levels due to plumbing corrosion. According to the Centers for Disease Control and Prevention (CDC), it is recommended to flush water from household faucets for at least 15 seconds prior to use, and to use cold water for cooking, as hot water has a higher dissolved copper content (Centers for Disease Control and Prevention, 2015).

Copper can be removed from drinking water using various analytical techniques such as reverse osmosis, ultrafiltration, and adsorption. Reverse osmosis is used to purify water from macromolecules and non-dissolved water contaminants. It employs a permeable membrane, allowing only non-charged particles to pass through; hence removing any ions or big particles, and even bacteria, from consumable water (Warsinger et al., 2016). During reverse osmosis, an artificial pressure is applied to prevent the natural flow of solute from an area of high concentration to one of low concentration. The membranes used for reverse osmosis do not possess any pores, but rather function solely based on chemical charge (Baker, 2004; Baker & Wijmans 1995). The disadvantage of using these non-porous membranes is that they waste too much water that cannot be recovered (Freeman, 1995; Zhu et al., 2013). Another technique, known as ultrafiltration, is also used to purify consumable water and remove copper. Ultrafiltration uses a membrane system to separate or extract contaminants based on molecular weight, rather than size. This system can effectively remove macromolecules the size of 103 to 106 Daltons, and can achieve 90% - 100% pathogen removal as required by water quality regulatory standards (Crystal Quest Water Filters, 2019). Ultrafiltration is efficient in removing water contaminants, and is desirable, as it does not require the use of chemicals. The only disadvantage to using ultrafiltration is that the membranes used are very fragile and susceptible to damage, leading to high cost of replacing the filters (Edwards et al., 2001). A third filtration process is known as adsorption, during which a solid surface is utilized to store or carry liquid molecules. It serves as a cheaper and more efficient alternative to traditional filtration systems (Aydin et al., 2008).

1.2.2. Lead

Lead is mainly used in construction of buildings and batteries. Lead poisoning can damage the nervous system and cause brain disorders (Canfield et al., 2003). Children, in particular, absorb more lead than adults due to their growing bodies. Infants and children under the age of six are most susceptible to the toxic effects of lead, which can enter our drinking water from household plumbing or service lines. The EPA requires that the lead level must not exceed 15 parts per billion (ppb). In order to prevent lead from entering our water source, water mains and pipes should be replaced by a lead-free material, such as Polyvinyl Chloride (PVC). Wastewater often has high quantities of lead produced by factories such as electronics assembly plants, battery recycling plants, and circuit board factories.

The most widely used technique to remove lead from water is through sand filtration. In this technique, solids can be separated from fluids by using surface filters and depth filters. Surface filters capture the solids on a permeable surface while depth filters intercept the solids within a porous body of material. The latter is more widely used to separate small amounts of lead from water. Coagulation and ion exchange are two other techniques for the removal of lead from water. During coagulation, aluminum sulfate (alum) is added to water to clump the lead particles together, enabling them to settle out of the water or be removed by filtration. In ion-exchange, resins, which contain small beads, are used to purify water and get rid of lead ions, by replacing them with non-toxic ions such as sodium and potassium. The best way to remove lead from water is through reverse osmosis, during which water is pushed through a series of filters and the membrane system filters out lead and other contaminants, allowing only water to pass through (ESP Water Products, 2019).

Older homes tend to have lead in the service pipes, which carry city water to communities living on the same street. As changing pipes can be costly, communities with lower household incomes are unable to invest in newer pipes. Hence, older neighborhoods with lower household income are likely to have a higher lead content in their tap water.

1.3. Total Hardness of Water

The State of Tennessee has hard water, which is defined as water that has a high content of minerals or solid chemical compounds. Some of these minerals, such as calcium and magnesium, seep into water systems as water passes through limestone. Although drinking moderately hard water can be beneficial to human health, high concentrations of minerals in water can have adverse health and economical effects. According to EPA standards, 0 - 60 mg/L of calcium and magnesium in water is considered soft water, 61 - 120 mg/L is considered moderately hard water, 121 - 180 mg/L is hard water, and anything above 180 mg/L is considered very hard water (USGS Science for a Changing World, 2019). One of the indicators of water's hardness is its inability to produce soap lather (Royal Society of Chemistry, 2019). Instead, a white residue (solid precipitate) forms due to the reaction of sodium stearate in soap with calcium in the water to form calcium stearate, $(C_{17}H_{35}COO)_2Ca$.

$$2C_{17}H_{35}COO^{-}(aq) + Ca^{2+}(aq) \rightarrow (C_{17}H_{35}COO)_2Ca(s)$$

Significant differences exist in the consumption of magnesium obtained from water. Soft-water drinkers have been shown to consume 2.3 mg of magnesium compared to hard-water drinkers consuming 52.1 mg of magnesium (Neri et al., 1985). According to the Department of Health, it is recommended that an average adult should consume 400 - 420 mg of magnesium for males and 310 - 360 mg of magnesium for females. In addition, both males and females are required to obtain 1300 mg of calcium, daily (National Institutes of Health, Office of Dietary Supplements, 2016; National Institutes of Health, Office of Dietary Supplements, 2018). Magnesium, an abundant mineral in the human body, is a cofactor which regulates various enzymatic processes and is involved in biochemical and signal transduction (Jahnen-Dechent & Ketteler, 2012; US National Library of Medicine, 2019). Calcium is required for bone development, sustainability of bone, hormonal balance and secretion, metabolic functions, and cardiovascular health (Cohen, 2019; Office of the Surgeon General, US, 2004). Inadequate levels of magnesium and calcium can have adverse health effects.

Although hard water has been shown to have some health benefits, it can have significant economic effects due to calcium and magnesium built-up in water pipes. This build-up can lead to pipe clogging and bursting. In addition to pipes, boilers and pasteurization systems can also fail due to overheating of instrument components brought about by the pipe clogs.

2. Materials and Methods

2.1. Data Collection

Secondary data was collected to obtain the 2017 yearly water safety report for each county in Tennessee. Additional information was obtained from each county's water service office, that was not provided on the yearly water safety report. Data including average annual household income was obtained from the United States Census Bureau, which was compiled and published in 2010. This data is about 9 years old, because census is carried out once every ten years, and the next census data will be published in 2020.

2.2. Statistical Analysis

After the compiling the information, the water quality data was prepared for descriptive statistical analysis. Histograms were used to illustrate the levels of copper and lead levels in different counties in Tennessee. Furthermore, 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 annual copper and lead levels detected in the drinking water of different counties in Tennessee are listed in **Table 2**. The copper level in Anderson county has been measured at 0.1 parts per million (ppm), which is well below the limit set at 1.3 ppm by the EPA. Similarly, the copper levels of the other counties are also below the EPA limits. According to the Annual Water Safety Report, detected copper levels are due to the leaking of wood preservatives, eroding of natural

Table 2. Annually detected copper and lead levels in different counties in Tennessee.

County	Copper (ppm)	Lead (ppb)
Anderson	0.1	7.2
Carter	0.294	3
Cumberland	0.06	2
Davidson	0.15	1
Dekalb	0.0345	1.41
Dyer	0.02029	7.8
Hamilton	0.114	2
Jackson	0.129	3
Knox	0.033	0.5
Madison	0.0427	1.23
Maury	0.106	2
Montgomery	0.27	1.5
Putnam	0.079	5
Rutherford	0.157	2.57
Shelby	0.33	8.63
Sullivan	0.2	2.4
Sumner	0.084	1.27
Williamson	0.082	0.5

deposits, and the corroding of plumbing system in the household (Norris Water Commission, 2018). The reported levels of lead in various counties are higher than the copper levels, but are still within the federal and state-legislated amounts of 15 parts per billion (ppb). Lead typically occurs due to erosion of old plumbing systems and natural deposits. The water turbidity data for each county was collected and found to be well below 1%, as mandated by local and federal legislations. Turbidity is typically resolved via the use of coagulants or through sedimentation.

As listed in **Table 2**, Shelby, Carter, and Montgomery counties appear to have highest levels of copper, while Dyer, Knox, and DeKalb counties have the lowest levels of copper. Shelby, Dyer, and Anderson counties have the highest detected levels of lead, while Knox and Williamson counties have the lowest lead levels. **Figure 1** provides a side-by-side comparison of the copper and lead levels among the different counties within Tennessee. It can be seen that the levels of copper are much lower than lead.

Data related to total water hardness was collected for each county and compared to the corresponding average household income and population, as listed in **Table 3**. The hardness of water refers to the amount of dissolved minerals, typically calcium and magnesium. It was determined that water from the Cumberland River is much harder than water obtained from other river sources.

Cumberland River serves as the primary water source for the Tennessee's capital Nashville and its surrounding areas. According to Table 3, water hardness is the greatest for Williamson county, at 139 mg/L. The average household income of

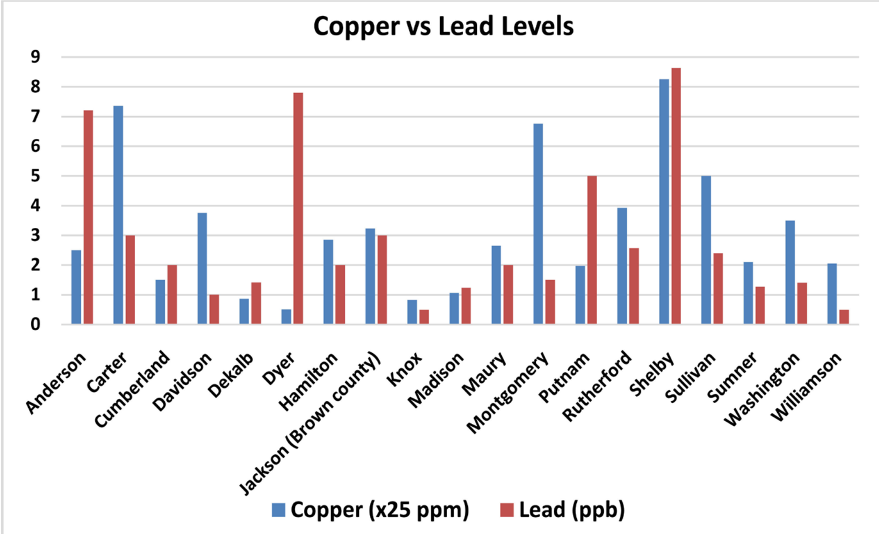

Figure 1. Differences in copper and lead levels among different counties in Tennessee.

Table 3. Demographics and water hardness among different counties in Tennessee.

County	Population	Average Household Income	Water Hardness (mg/L)
Anderson	75,129	$44,650	90
Carter	57,424	$31,173	61
Cumberland	56,053	$36,813	76
Davidson	626,681	$56,084	115
DeKalb	18.723	$34,863	70
Dyer	38,335	$36,856	76
Hamilton	336,463	$45,408	94
Jackson	11,509	$32,722	63
Knox	432,226	$46,759	92
Madison	98,294	$40,178	80
Maury	80,956	$46,278	95
Montgomery	172,331	$48,930	98
Putnam	72,321	$35,185	70
Rutherford	262,604	$53,770	87
Shelby	927,644	$44,705	71
Sullivan	156,823	$39,957	59
Sumner	183,545	$54,916	92
Washington	336,463	$41,256	60
Williamson	205,226	$87,832	139

Williamson county is the highest ($87,832) while that of Carter county is the lowest ($31,173). Figure 2 shows a graphical comparison of the average household income to the total water hardness. The total hardness of water does not seem to correlate with the average household incomes of the counties.

The average household incomes were also compared to the copper and lead levels to determine whether more affluent counties had access to cleaner water when compared to less affluent counties. As shown in Figure 3, the counties with higher average household incomes seem to typically have lower levels of detectable copper compared to counties with lower average household incomes. A similar correlation exists between average household income and lead levels.

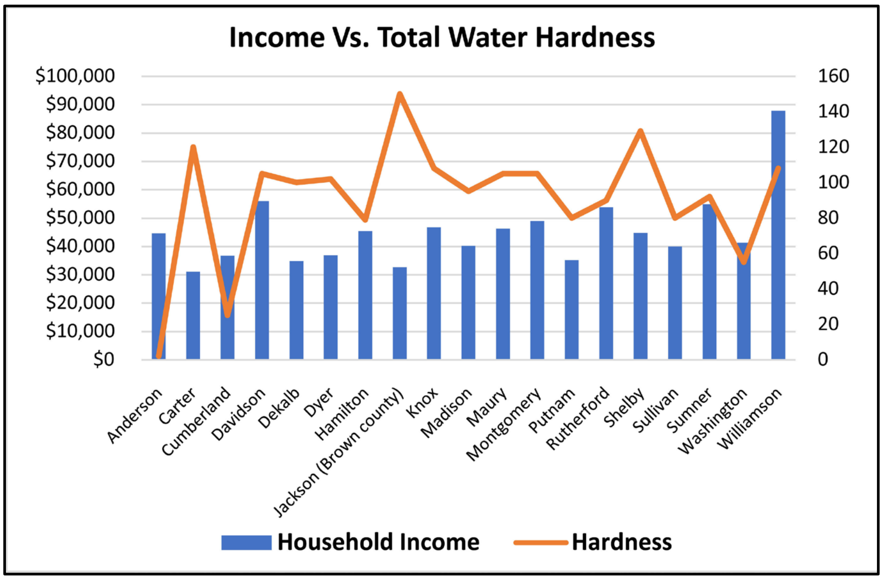

Figure 2. Differences in average household income among different counties within Tennessee as it correlates to total water hardness.

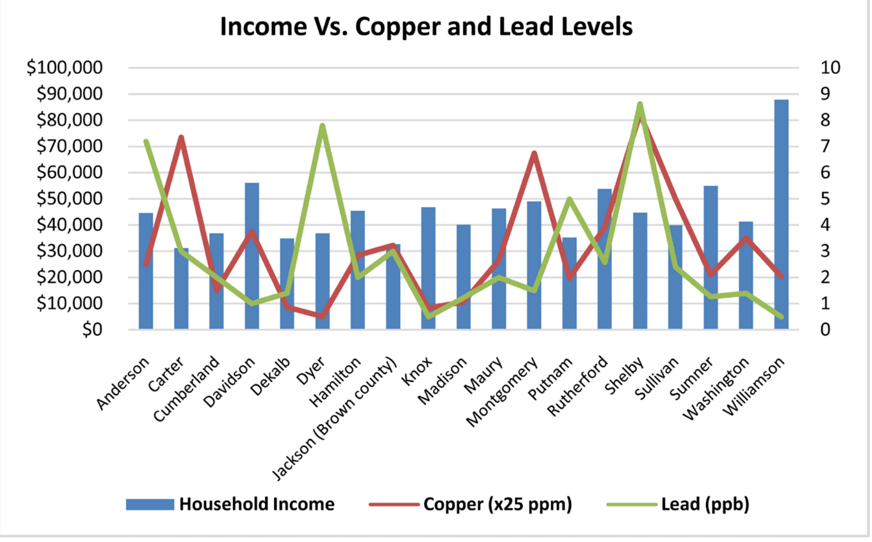

Figure 3. Differences in copper and lead levels among different counties in Tennessee, as related to average household income.

4. Conclusion

Analysis of drinking water for trace metal contamination is an important step in ensuring both human and environmental health. Several counties in the State of Tennessee were examined in order to determine the levels of copper and lead in drinking water, water hardness as well as their correlation to the socioeconomic background of the residents. It was determined that, although several counties with typically lower average household incomes had higher copper and lead levels in their drinking water, these effects were random, and the contaminants remained below the EPA and state-regulated guidelines. Water obtained from the Cumberland River was found to be much harder than water obtained from other river sources. However, the total hardness of water had no correlation with the average household income of the counties in Tennessee.

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Conflicts of Interest

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

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Abbreviations

EPA; Environmental Protection Agency
WHO; World Health Organization
CCL; Contaminant Candidate List
SDWA; Safe Drinking Water Act
CDC; Centers for Disease Control and Prevention
ppm; Parts per Million
ppb; Parts per Billion
PVC; Polyvinyl Chloride