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A Descriptive Study of Well Water Contaminants in Georgia from 2010-2022

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Abstract

Introduction: Safe, reliable, and clean drinking water sources are a basic necessity; however, chemical contamination of private wells has plagued Georgia. More than 1.7 million individuals in Georgia rely on private wells for drinking water; nonetheless, wells are not under mandated regulations as municipal water supplies. Well water can contain chemical contaminants such as arsenic, uranium, lead, nitrate-nitrogen, and radon that can impact health when above the federal Maximum Contaminant Limit (MCL). In Georgia, previous studies suggested that the variation of soil and rock in a physiographic province (region) plays an essential role in the quality of private well water. There is a need to understand the distribution of these chemical contaminants above the federal MCL and how the different geologies in each physiographic province might influence such concentrations. Therefore, this study aimed to examine the distribution of arsenic, uranium, radon, nitrate-nitrogen, and lead concentrations above the federal MCL in private well water and examine an association of contamination with physiographic provinces in Georgia specifically by utilizing private well water data collected by the University of Georgia's Agricultural and Environmental Services Laboratories (AESL).

Methods: The University of Georgia's AESL tested samples of private well water upon the request of residents in Georgia between January 2010 and March 2022. Samples were tested for arsenic, uranium, radon, nitrate-nitrogen, and lead. The United States Geological Survey collected data from Fenneman's "Physical Divisions of the United States," which is based on eight major divisions, 25 provinces, and 86 sections representing distinctive areas having common topography, rock types and structure, and geologic and geomorphic history originally published on January 1, 1946. Bivariate associations between the physiographic provinces and the proportion of arsenic, uranium, radon, nitrate-nitrogen, and lead concentrations detected in

private well water samples above the federal MCL were tested using cross-tabulation with the chi-square option (χ^2). Alpha was set at $p < .05$ for results to be considered statistically significant.

Results: In Georgia, over 26,000 well water samples were collected and tested for a least one chemical contaminant from 2010 through 2022. The majority of well water samples were tested for nitrate-nitrogen contamination (n=14,384). Samples tested for arsenic and nitrate-nitrogen with concentrations exceeding the MCL appeared more often in the Coastal Plain province. Samples tested for lead with concentrations exceeding the MCL appeared more often in the Blue Ridge province. Samples tested for radon and uranium with concentrations exceeding the MCL appeared more often in the Piedmont province. Cross-tabulation with the chi-squared (χ^2) option indicated associations between physiographic provinces and the proportion of private well water samples containing arsenic concentrations exceeding the federal MCL in the Coastal Plain, $\chi^2(3) = 95.53$, $p = <.001$, and the proportion of private well water samples containing nitrate-nitrogen concentrations exceeding the federal MCL in the Coastal Plain, $\chi^2(4) = 11.56$, $p = .021$.

Conclusion: Elevated concentrations of arsenic, uranium, radon, nitrate-nitrogen, and lead can cause adverse conditions such as chronic toxicity, liver, kidney, and intestinal damage, anemia, and cancer that can impact health. Understanding the geological factors behind poor well water quality will promote public health initiatives that increase public awareness and provide opportunities to maintain healthy well water quality in Georgia.

Keywords: Georgia, well water, contamination, physiographic provinces, water quality, geology

Author's Statement Page

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Angelique Willis

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Chapter I

Introduction

Public health professionals have long recognized the importance of having a safe and reliable source of drinking water to reduce environmental chemical contaminants to humans via drinking water. Specifically in Georgia, Congress passed primary legislation to address water pollution control in 1957. Since the late 1960s, Georgia has conducted long-term water quality monitoring of nearly 70 streams at strategic locations throughout Georgia (Booth, 2022). In 1972, the Clean Water Act (CWA) was enacted by Congress, which aimed to restore and maintain the chemical, physical and biological integrity of the Nation's waters, and to achieve, wherever attainable, the goal of providing for the protection and propagation of fish, shellfish, wildlife, and providing for recreation in and on the water (Georgia Environmental Protection Division, n.d.). In response to the CWA being enacted in 1972, the Georgia Environmental Protection Division (GEPD) and the United States Environmental Protection Agency (EPA) jointly identified both point and nonpoint sources of pollution for municipal drinking water supplies, recreation water supplies, fishing water supplies, wild river water supplies, scenic river water supplies, and coastal river water supplies to control for pollution that would be harmful to human health (Georgia Environmental Protection Division, n.d.).

Further, in 1974, the Safe Drinking Water Act (SDWA) was enacted by Congress, which aimed to establish minimum standards for state programs to protect underground sources of drinking water from endangerment and establish minimum standards to protect tap water, which required all owners or operators of public water systems to comply with primary health-related standards (United States Environmental Protection Agency, 2021a). Although the SDWA was passed to address water quality issues for municipal drinking water supplies, there are no federal

or state regulations for water testing to maintain private wells in Georgia (Georgia Department of Public Health, 2018). It is the private well water owner's responsibility to make sure their water is safe to drink. Nonetheless, numerous households that rely on private well water do not routinely test their well water as suggested by their local health departments, thus, missing the opportunity to monitor an abundance of chemical contaminants that can go undetected in their drinking water (Association of Public Health Laboratories, 2019).

To increase private well water testing among Georgians, in the late 1990s, the University of Georgia's Extension program, which comprises the Agricultural and Environmental Services Laboratories (AESL), provided private well water testing of chemical contaminants upon the request of residents in Georgia (University of Georgia, n.d.). Since implementing the University of Georgia's Extension program, the AESL has offered basic physico-chemical water tests and an expanded list of chemicals for water tests. The basic tests include acidity (pH) and Hardness, Phosphorus (P), Potassium (K), Calcium (Ca), Aluminum (Al), Boron (B), Chromium (Cr), Copper (Cu), Iron (Fe), Magnesium (Mg), Manganese (Mn), Molybdenum (Mo), Nickel (Ni), Silica (SiO_2), Sodium (Na) and Zinc (Zn) in well water samples (University of Georgia, n.d.). The expanded water tests for basic contaminants as well as anions such as Chloride (Cl), Fluoride (F), Nitrate-Nitrogen (NO_3-N), Phosphate (PO_4), Sulfate (SO_4), Arsenic (As), Lead (Pb), Radon (Rn), Uranium (U), soluble salts, and alkalinity (University of Georgia, n.d.). As a result of these tests being offered to the public, the University of Georgia's Extension program has been able to track private well water quality in Georgia, especially for the chemical contaminants arsenic, uranium, radon, nitrate-nitrogen, and lead.

Chemical contaminants and geological regions in Georgia

According to Clarke and McConnell, Georgia's geology consists of vastly different

geological provinces (regions) containing unique minerals, rock types, and landforms relative to each other that may influence private well water quality. These geological regions in Georgia are classified into five distinct physiographic provinces: the Appalachian Plateau, Blue Ridge, Coastal Plain, Piedmont, and Valley and Ridge. Although anthropogenic activities and sources such as fertilizer use, mining, plumbing, and the combustion of fossil fuels can influence human environmental exposures to elevated concentrations of chemical contaminants in private well water supplies, the diverse geology in Georgia's physiographic provinces can influence these exposures as well, which can significantly differ from province to province (Clarke & McConnell, 1986). While there is evidence that arsenic, uranium, radon, nitrate-nitrogen, and lead exist in Georgia's private well water supplies, concentrations of such chemical contaminants found in Georgia's private well water supplies and how the different geologies in each physiographic province might influence such concentrations is still unclear.

Study objectives

Given this background, this study aimed to examine the distribution of arsenic, uranium, radon, nitrate-nitrogen, and lead concentrations above the federal Maximum Contaminant Level (MCL) in private well water and examine an association of contamination with physiographic provinces in Georgia specifically by utilizing private well water data collected by the University of Georgia's AESL. Understanding how the geology in each physiographic province in Georgia contributes to elevated concentrations of arsenic, uranium, radon, nitrate-nitrogen, and lead in private well water supplies can provide insight into the geological factors that contribute to poor well water quality in Georgia, thus increasing awareness, education, and informing public health policy that improves the quality of private well water for Georgians.

Chapter II

Literature Review

National water quality regulations

In 1972, the Clean Water Act (CWA) established the basic structure for regulating discharges of pollutants into the waters of the United States and regulating quality standards for surface waters (United States Environmental Protection Agency, 2022e). In 1974, the Safe Drinking Water Act (SDWA) was established to protect the quality of drinking water in the United States, focused on all waters actually or potentially designed for drinking use, whether from above ground or underground sources (United States Environmental Protection Agency, 2021a). Although these standards were established for various drinking water sources, the EPA does not regulate private wells nor provide recommended criteria or standards for private wells (United States Environmental Protection Agency, 2022d).

In the United States, more than 43 million individuals rely on private wells as their source of drinking water (Water Resources, 2019). Private well owners are responsible for maintaining the safety and quality of their well water. Federal regulations under the SDWA for public water supplies, although not directly applicable to the regulation of private wells, provide proper concentration standards for evaluating water quality from private wells (Water Resources, 2019). Chemical contaminants such as arsenic, uranium, radon, nitrate-nitrogen, and lead are among the most common chemical contaminants that can be measured as indicators of poor well water quality. Wells are susceptible to these contaminants because they are often improperly constructed, close to contaminant sources, or contain water-bearing rock that naturally comprises them. Understanding how geology influences the chemical contamination of private well water can increase awareness, education, and implementation of interventions to improve private well

water quality. The literature review provided herein explains the importance of how geology influences chemical contamination in private well water in the Southern United States, specifically in Georgia.

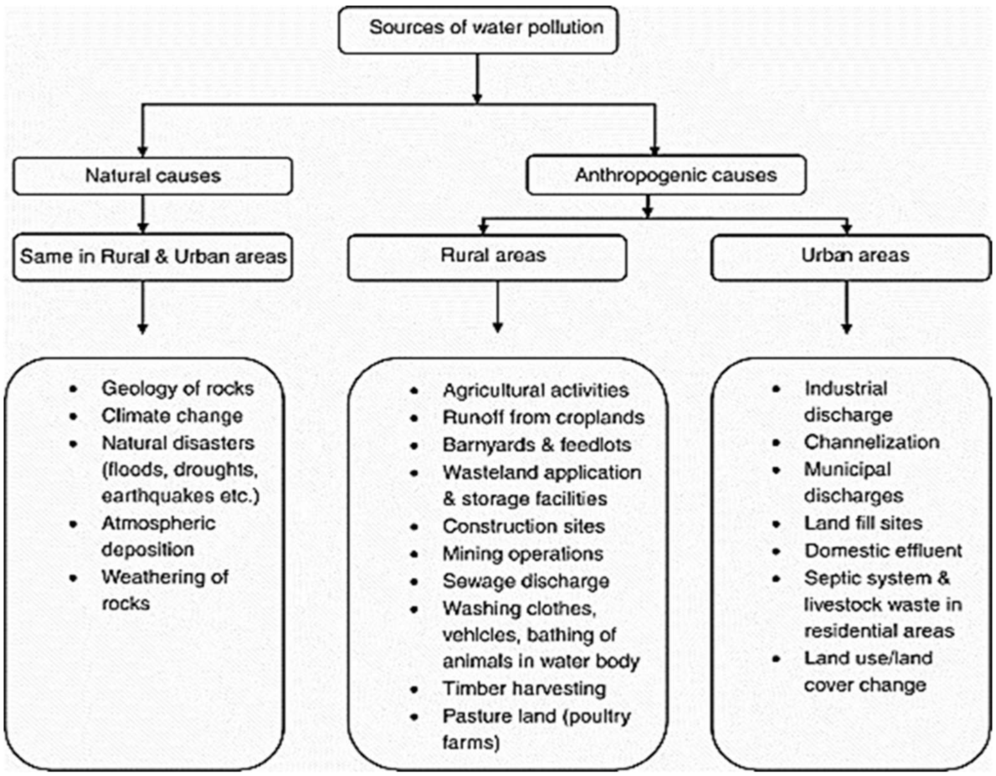
Anthropogenic activities that introduce chemical contaminants into the natural environment

Anthropogenic activities are human actions and behaviors that directly or indirectly cause environmental contamination and change (United States Geological Survey, 2015). Anthropogenic activities that cause contamination and change to the natural environment include farming, fertilizer use, field irrigation, oil and gas production and storage, chemical manufacture and storage, pollution, burning fossil fuels, deforestation, and the release of fuel particles used for flying airplanes (United States Environmental Protection Agency, 2022b). As a result of these types of anthropogenic activities, heavy metals such as lead and chemical contaminants such as nitrate-nitrogen can enter the environment and infiltrate into the ground or soil, causing groundwater contamination.

Furthermore, different anthropogenic activities occur more often in urban or rural areas, affecting environmental change and contamination in those settings. As shown in Figure 1, groundwater quality can be affected by agricultural activities, sewage discharge, and mining operations that mainly occur in rural areas, or municipal discharges, landfill sites, and industrial discharges that mainly occur in urban areas (Khatri & Tyagi, 2015). Research implies that agricultural activities such as farming and fertilizer use introduce nitrate-nitrogen into the environment, which seeps into the soil and contaminates groundwater (Kallenbach & Evans, 2014). Also, research indicates that industry activities such as burning fossil fuels and industrial discharge introduce lead into the environment, which seeps into the soil and contaminates groundwater (Brelje & Race Labs, 2019).

Figure 1.

Flowchart showing natural and anthropogenic sources of water pollution in rural and urban areas.



Note. This figure shows the natural and anthropogenic causes of water contamination in rural and urban settings. From Khatri & Tyagi, 2015. (https://doi.org/10.1080/21553769.2014.933716).

Naturally occurring chemical contaminants in the environment

In the natural environment, chemical contaminants can be naturally occurring, meaning it was not manufactured or created by anthropogenic activities (Agency for Toxic Substances and Disease Registry, 2018a). Naturally occurring sources of chemical contaminants in the environment include soil, groundwater, and geology of rocks (Figure 1). Arsenic, uranium, and radon are naturally occurring contaminants in the environment. Anthropogenic activities that manipulate the environment, such as mining operations and drilling wells to get water, can create conditions allowing exposure to these naturally occurring contaminants (Agency for Toxic

Substances and Disease Registry, 2018b). These chemical contaminants can enter groundwater if released into the environment.

Anthropogenic chemical contaminants that degrade water quality causing serious illness

Nitrate-nitrogen

Nitrate-nitrogen refers to the nitrogen portion of the total nitrate found in a sample (Land Air Water Aotearoa, 2021). Nitrate is a common, naturally occurring chemical compound made of the elements nitrogen (N) and oxygen (O) (Land Air Water Aotearoa, 2021). Nitrogen is a nutrient that occurs naturally in the soil in organic forms from decaying plant and animal residues. It is also present in fertilizer applied for lawn, garden, and crop care (Skipton et al., 2013). Feedlots, animal yards, septic systems, and other waste treatment systems are additional sources of nitrate and nitrogen carried in waste (Skipton et al., 2013). Nitrate-nitrogen is odorless, tasteless, and colorless and infiltrates drinking water when rain or irrigation water carries nitrate down through the soil into groundwater that may come from anthropogenic sources such as sewage and fertilizer or naturally occurring nitrogen sources (Washington State Department of Health, n.d.). Research has shown potential associations between nitrate-nitrogen exposure and health effects such as increased heart rate, nausea, headaches, abdominal cramps, gastric cancer, and congenital disabilities while pregnant (Minnesota Department of Health, n.d.; Skipton et al., 2013). Also, studies have shown that infants who drink water with high nitrate-nitrogen levels may develop a serious health condition called methemoglobinemia or “blue baby syndrome” (Washington State Department of Health, n.d.). As a result of the severe adverse health outcomes associated with nitrate-nitrogen exposure in drinking water, the EPA set the federal Maximum Contaminant Level (MCL) for nitrate-nitrogen in drinking water to 10 mg/L (United States Environmental Protection Agency, 2022a). Although these standards were

established to protect human health, the MCL for nitrate-nitrogen only applies to public water supplies classified as either community or non-community, not private wells (Skipton et al., 2013).

Lead

Lead is a naturally occurring element found in small amounts in the earth's crust, and can be found in the air, the soil, the water, and inside homes (United States Environmental Protection Agency, 2022f). However, human exposure to lead mostly comes from anthropogenic sources, including the use of fossil fuels such as leaded gasoline, some types of industrial facilities, and lead-based paint in homes (United States Environmental Protection Agency, 2022f). Nearly all lead in drinking water comes from water that stands idle in corroded pipes, plumbing, and components in well water systems that contain lead (Minnesota Department of Health, 2019). Also, lead can enter groundwater from industry, mining, gasoline, and coal particles that stick to the soil and trickles down to groundwater (Virginia Department of Health, n.d.). Since lead is colorless, odorless, and flavorless, those exposed to lead in drinking water could potentially be exposed to high amounts of lead, which can cause adverse health outcomes. Research has shown that ingestion of lead through drinking water can cause cardiovascular problems, decreased kidney function and reproductive problems in adults, reduced growth of the fetus and premature birth in pregnant women, and anemia, slowed growth, and lower IQ in children (United States Environmental Protection Agency, 2022c). In an attempt to address the role of plumbing in the contribution of lead in drinking water, the EPA established a Treatment Technique (TT) rather than setting an MCL for lead in drinking water. A TT is an enforceable procedure or level of technological performance that water systems must follow to ensure contaminant control; however, this standard does not apply to private wells. (United States Environmental Protection

Agency, 2022c). A TT was established for lead mainly because lead is generated after the water leaves the water distribution plant.. The TT for lead requires Community Water Systems (CWS) to control the corrosivity of the drinking water (United States Environmental Protection Agency, 2022c). Since a TT is used for regulatory standards for lead, if more than 10% of tap water samples exceed the action level of 15 micrograms per liter (µg/L), CWS must take additional steps to reduce the amount of lead in drinking water (United States Environmental Protection Agency, 2022c).

Naturally occurring chemical contaminants that degrade water quality causing serious illness

Arsenic

Arsenic is a natural component of the earth's crust and is widely distributed throughout the environment in the air, water, and land (World Health Organization, 2018). Nearly all arsenic in drinking water originates from natural rock formations in its inorganic form. As water flows through these natural rock formations, it can dissolve inorganic arsenic and carry it into underground aquifers or underground rocks that hold groundwater, streams, and rivers that may become drinking water supplies (Washington State Department of Health, 2011).

In groundwater, inorganic arsenic usually occurs in two forms: trivalent arsenic (As+3, or arsenite), pentavalent arsenic (As+5, or arsenate), or both (Pure Water Occasional, n.d.). Trivalent arsenic is arsenic with three fewer electrons than protons, giving it a plus three positive charge; pentavalent arsenic is arsenic with five fewer electrons than protons, giving it a plus five positive charge (Dartmouth, n.d.). Depending on the constituents of groundwater, such as acidity (pH), oxygen, iron, and other molecules that may be present, these two forms can be readily converted back and forth in groundwater (Dartmouth, n.d.). Although both forms cause severe

illness in humans, trivalent arsenic is more harmful and difficult to remove from water (Pure Water Occasional, n.d.).

Since inorganic arsenic is odorless and tasteless, many individuals who consume drinking water with this chemical contaminant often do not realize it. Prolonged exposure to inorganic arsenic has been linked to numerous adverse health outcomes, including nausea, vomiting, stomach pain, blindness, partial paralysis, and cancer of the bladder, lungs, skin, kidneys, liver, and prostate (United States Environmental Protection Agency, 2021b). As a result of the severe adverse health outcomes associated with inorganic arsenic exposure in drinking water, the EPA adopted an MCL, or the highest level of a contaminant that is allowed, for arsenic in CWS; however, this standard does not apply to private wells (United States Environmental Protection Agency, 2021b). In 2001, the MCL for arsenic in drinking water was 0.05 milligrams per liter (mg/L); however, since research proved arsenic to be detrimental to health, the MCL for arsenic was changed to 0.01 mg/L (United States Environmental Protection Agency, 2021b).

Uranium

Uranium is a natural and radioactive component of rocks, soil, air, and water and occurs in the environment as minerals but not as a metal (Water Quality Association, n.d.). Uranium infiltrates drinking water when groundwater dissolves minerals that contain uranium in the bedrock underneath the ground (Connecticut Department of Public Health, 2006). In drinking water, uranium does not have a taste, smell, or color and can lead to prolonged exposure to this chemical contaminant. Research shows that prolonged exposure to ingesting uranium has been linked to kidney toxicity and an increased risk of cancer (Water Quality Association, n.d.). Also, uranium can decay into other radioactive substances, such as radium or radon, which can cause cancer with prolonged exposure over time (Water Quality Association, n.d.). As a result of the

severe adverse health outcomes associated with uranium exposure in drinking water, the EPA set the MCL for uranium in drinking water to 0.03 mg/L (United States Environmental Protection Agency, 2021c). Although these standards were established to protect human health, the MCL for uranium only applies to CWS, not private wells (United States Environmental Protection Agency, 2021c).

Radon

Radon is a gas with no color, odor, or taste and comes from the natural radioactive breakdown of uranium in the ground (United States Environmental Protection Agency, 2014). Radon infiltrates drinking water when groundwater dissolves uranium minerals that contain radon in the bedrock underneath the ground (Kansas State University, n.d.). Once radon dissolves and accumulates in groundwater, it can escape from the water brought inside the home when it is used for showering or cooking (United States Environmental Protection Agency, 2014). Research suggests prolonged exposure to radon from drinking water has been linked to an increased risk of lung and stomach cancer (Kansas State University, n.d.). As a result of the severe adverse health outcomes associated with radon exposure in drinking water, the EPA recommended requiring CWS to provide drinking water with radon levels no higher than 4,000 picocuries per liter of air (pCi/L), which contributes to about 0.4 pCi/L of radon to the air in the home environment. However, currently, there is no federally enforced drinking water MCL for radon in CWS or private wells (United States Environmental Protection Agency, 2014).

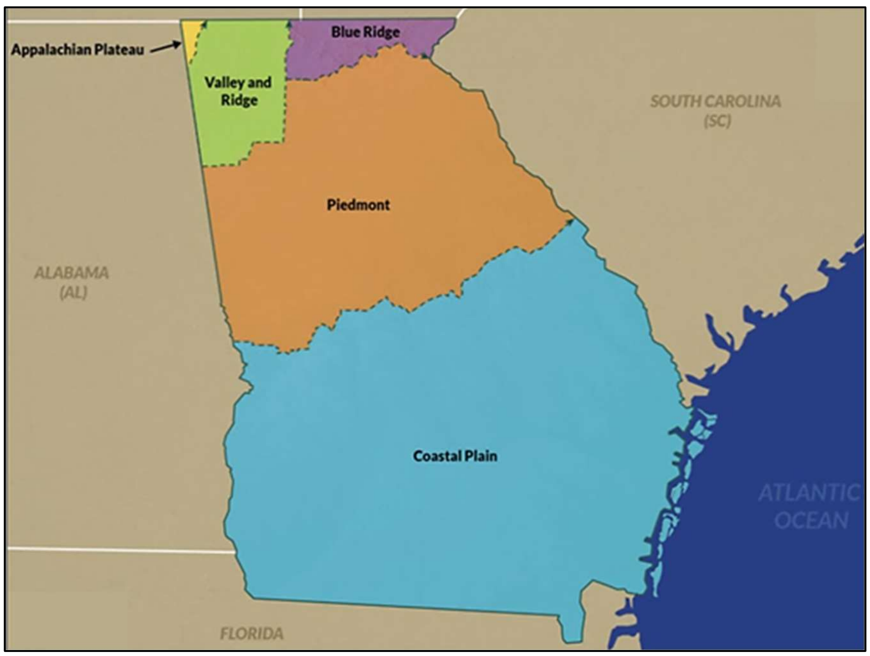
Influence of geology on ground and well water quality in the state of Georgia

Georgia is located in the Southern United States and is geographically diverse. As shown in Figure 2, Georgia has five distinct physiographic provinces: the Appalachian Plateau, Blue Ridge, Coastal Plain, Piedmont, and Valley and Ridge. According to Miller & Robinson,

physiographic provinces in the southeastern United States contain predominant types of rocks (Miller & Robinson, 1995). The Cumberland Plateau province, currently known as the Appalachian Plateau province, comprises horizontal layers of sandstone, shale, and limestone sedimentary (Miller & Robinson, 1995).

Figure 2.

The Physiographic Provinces in Georgia.



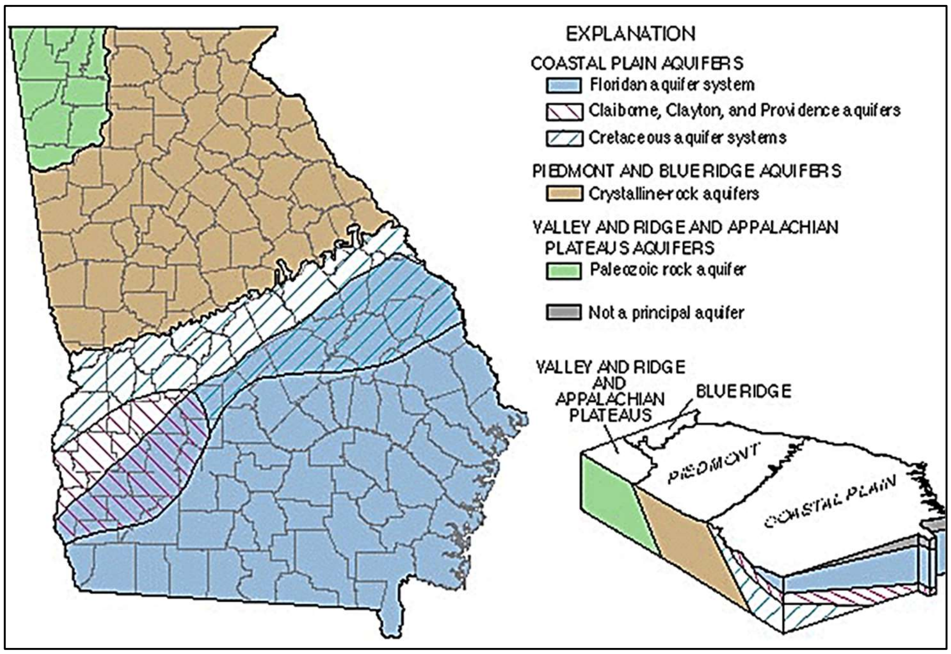
Note. This figure shows the five physiographic regions or physiographic provinces in Georgia. From Georgia Public Broadcasting, 2016. (https://artsandculture.google.com/asset/physiographic-regions-of-georgia-georgia-public-broadcasting/tAHuQ54Owanphw).

The Blue Ridge and Talladega Mountains province comprises uplifted metamorphic and igneous rocks with wide aprons of colluvium, while the Valley and Ridge province comprise folded and tilted sedimentary rocks with sandstone ridges and limestone valleys with wide aprons of colluvium (Miller & Robinson, 1995). The Piedmont province comprises varying zones of deeply weathered metamorphic rocks with lesser areas of sedimentary and igneous rocks (Miller & Robinson, 1995). The Coastal Plain province comprises unconsolidated water, ocean, and wind-deposited sediments (Miller & Robinson, 1995).

Within Georgia, there are six principal aquifers, as shown in Figure 3, which are located within each physiographic province: the Floridan aquifer system, the Claiborne and Clayton aquifers, the Cretaceous aquifer system, and the Paleozoic and Crystalline rock aquifers (Clarke & McConnell, 1986).

Figure 3.

Area of use of principal aquifers and generalized diagram showing aquifers and physiographic provinces in Georgia.



Note. This figure shows the six principal aquifers in each physiographic province in Georgia. From United States Department of the Interior and United States Geological Survey, 1997. (https://pubs.usgs.gov/fs/FS-010-96/).

These aquifers vary in natural groundwater quality as they are linked to different geological strata. The Floridian aquifer system (Coastal Plain physiographic province) consists of limestone, dolomite, and calcareous sand and yields calcium bicarbonate water, in which groundwater in the Floridan aquifer system may contain natural radioactive materials (Clarke & McConnell, 1986). The Claiborne Aquifer System (Coastal Plain physiographic province) consists of sand and sandy limestone. The Clayton Aquifer System (Coastal Plain physiographic

province) primarily comprises limestone and calcareous sand (Clarke & McConnell, 1986). The Cretaceous Aquifer System (Coastal Plain physiographic province) contains sand and gravel. The Paleozoic Rock Aquifer System (Valley and Ridge and Appalachian Plateau physiographic provinces) consists of sandstone, shale, limestone, and dolomite, and water is stored in joints, fractures, and solution openings in the bedrock (Clarke & McConnell, 1986). The Crystalline Rock Aquifer System (Blue Ridge and Piedmont physiographic provinces) contains bedrock overlain by regolith (Clarke & McConnell, 1986).

Given the different geological traits of the physiographic provinces in Georgia, researchers have suggested that there may be an association between the quality of well water and groundwater and the geological traits found in each physiographic province. For instance, Clarke and McConnell suggested that compared to the Piedmont and Blue Ridge provinces, the Valley and Ridge and Coastal Plain provinces have loose soil that allows chemically contaminated water to permeate into the ground easily and replenish the aquifers and wells; hence, the potential for chemical contamination is more significant (Clarke & McConnell, 1986). In recharge areas of the Cretaceous aquifer system, extremely permeable, sandy soils provide little protection against leakage from surface waste impoundments and landfills, contaminating groundwater and well water. For the Floridan aquifer system, the risk of chemical contamination is greatest, where the soils are very permeable and sinkholes connect the aquifer with the land surface. In the Valley and Ridge province, the Paleozoic aquifers are susceptible to chemical contamination in areas where sinkholes have developed or where bedrock is exposed at the surface or is covered by a thin layer of soil. Lastly, in the Piedmont province, the Crystalline rock aquifers are vulnerable to chemical contamination where the protective layer of saprolite (weathered rock) is thin and permeable (Clarke & McConnell, 1986).

Similarly, Swain et al. suggested that there may be an association between the quality of well water and groundwater and the geological traits of the physiographic provinces in Georgia. Swain et al. suggested that the natural quality of groundwater in the Valley and Ridge physiographic province is affected by the residence time of water within the aquifer, depth of circulation, and mineral composition of the rock matrix (Swain et al., 1991). Moreover, Swain et al. suggested that the quality of groundwater in the Crystalline-rock regimes of the Piedmont and Blue Ridge physiographic provinces strongly affects the quality of the groundwater and, compared to all the natural contaminants found in groundwater, radionuclides or radon potentially poses the greatest threat to human health in Piedmont and Blue Ridge physiographic provinces (Swain et al., 1991).

Groundwater quality monitoring in the state of Georgia

For over 30 years, groundwater quality studies have been conducted in Georgia to monitor the overall water quality in the state. Beginning in 1986, Clarke and McConnel published a review of groundwater quality in Georgia that summarized characteristics of the variability of chemical contaminants from groundwater samples collected during 1938 through 1985 from Georgia's principal aquifers (Clarke & McConnell, 1986). In this report, the researchers used the median concentrations of chemical contaminants found in Georgia's principal aquifers to provide a descriptive analysis of specific chemical contaminants that exceeded or did not exceed the standards set by the EPA and the Georgia Environmental Protection Division (GEPD) for acceptable limits of chemical contaminants in drinking water. Groundwater in each of the principal aquifers had median concentrations of nitrate-nitrogen, chloride, iron, and dissolved solids that did not exceed the standards the GEPD and the EPA set. However, Clark and McConnell did not describe any potential relationship between groundwater

sample concentrations collected and the physiographic province in which the aquifer was in, nor did they describe any descriptive statistics on private well water samples found in Georgia's principal aquifers and how these samples may be associated with the physiographic province.

Furthermore, in 1991, Swain et al. published a review of regional aquifer systems in the physiographic provinces in the eastern and southeastern United States concerning their geology, hydrogeology, and water quality (Swain et al., 1991). In that report, groundwater quality was analyzed for chemical contaminants given the geologic attributes of where the groundwater was located in over 142,000 (square miles) in parts of New Jersey, Delaware, Pennsylvania, Maryland, the District of Columbia, Virginia, West Virginia, Tennessee, North Carolina, South Carolina, Georgia, and Alabama. Overall, the relationship between a contaminant in groundwater and geology was described for hardness, calcium, iron, magnesium, and dissolved solids; however, researchers did not conduct research analyses on private well water samples found in Georgia's principal aquifers and physiographic provinces nor describe a potential relationship that may exist between the two.

Well water quality monitoring in the state of Georgia

Nitrate-Nitrogen

In 1995, Tyson et al. published a review of the extent and distribution of nitrate-nitrogen contamination in 3,419 domestic well water samples in Georgia collected from 1989 through 1993 (Tyson et al., 1995). In that report, private well water samples were separated into six major land resource areas or physiographic provinces of Georgia (Blue Ridge, Limestone Valley, Sand Hills, South Coastal Plain, Southern Piedmont, and Atlantic Coast Flatwoods). Average concentrations of nitrate-nitrogen found in each major land resource area in Georgia were used to determine if that specific contaminant exceeded the standards set by the EPA for the acceptable

limit of nitrate-nitrogen in drinking water. The Atlantic Coast Flatwoods and the Limestone Valley had the highest average nitrate-nitrogen concentration in shallow wells at 3.3 mg/L each. Although researchers in this article provided a descriptive analysis of nitrate-nitrogen concentrations found in private well water samples in Georgia's major land source areas, a potential association between nitrate-nitrogen and the physiographic province was not described in detail. In fact, nitrate-nitrogen concentrations were associated with how shallow or deep a well was. Specifically, higher concentrations of nitrate-nitrogen in private well water samples were associated with shallow wells.

Furthermore, in 2003, Leeth et al. published a report that reviewed water testing of 156 wells from major aquifers in Georgia during 2001 (Leeth et al., 2003). The report indicated that average nitrate-nitrogen concentrations in the Floridan aquifer had increased since 1998, and a couple of wells had nitrate-nitrogen concentrations above the EPA's 10 mg/L drinking water standard. Like Tyson et al., Leeth et al. focused on nitrate-nitrogen concentrations of wells. However, instead of associating exceeding nitrate-nitrogen concentrations with how shallow or deep a well was or with the physiographic province the well water sample was taken, Leeth et al. examined if average concentrations of nitrate-nitrogen in the well for each major aquifer in Georgia were more or less than what was recorded in previous years. In this report, Leeth et al. found that average nitrate-nitrogen concentrations were higher than recorded in previous years.

Nitrate-nitrogen and lead

In 1997, Bush et al. published a report that reviewed the testing of 4,593 private well water samples collected by the University of Georgia's Agricultural and Environmental Services Lab (Bush et al., 1997). In this report, average concentrations of private well water monitoring results indicated that 2.9-7.4% of all wells tested contained elevated levels of nitrate-nitrogen,

and 0.7-8.4% of all wells tested contained elevated lead concentrations. Like Tyson et al., Bush et al. focused on describing a potential association between average nitrate-nitrogen concentrations in private well water that exceeded or did not exceed the standards set by the GEPD and the EPA with how shallow or deep a well was. In this article, Bush et al. found a potential association between lower average nitrate-nitrogen concentrations and deeper wells and elevated average nitrate-nitrogen concentrations and shallow wells. However, Bush et al. did not examine relationships between exceeding nitrate-nitrogen concentrations above EPA and GEPD standards in the private well water samples and the physiographic province where the private well water samples were taken.

Nitrate-nitrogen, lead, and copper

In 2005, Sonon et al. published a report that reviewed the private well water quality of 27,047 water samples collected from 1993 through 2004 from private drinking wells in Georgia (Sonon et al., 2005). In this report, Sonon et al. found that nitrate-nitrogen, lead, and copper were the primary chemical contaminants found in Georgia private well waters, and that nitrate-nitrogen above the EPA standards was found in 1-8% of the well samples, with greater occurrence in the physiographic provinces of Limestone Valley and Sand Hills. Also, Sonon et al. found that out of all samples tested for lead contamination, 2-8% of private well water samples had lead and copper concentrations above the EPA standards, with greater occurrence in water samples from Southern Piedmont and Sand Hills physiographic provinces (Sonon et al., 2005). While Sonon et al. provided a descriptive analysis of contaminant concentrations found in private well water samples in the major physiographic provinces of Georgia that exceeded the EPAs standard, a potential association between an exceeding concentration of a contaminant and the physiographic province in which the sample was taken, was not described in detail.

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Chapter III

Manuscript

1. Introduction

Safe, clean, and reliable drinking water sources are essential for good human health (World Health Organization, 2022). In the United States, to ensure drinking water sources are safe and clean for human consumption, the Safe Drinking Water Act (SDWA) was established to protect the quality of drinking water in Community Water Systems (CWS) (United States Environmental Protection Agency, 2022c). In conjunction with these laws, the Environmental Protection Agency (EPA) set federal Maximum Contaminant Limits (MCLs) for specific chemical contaminants in drinking water that pose the most severe risk to human health such as arsenic, uranium, radon, nitrate-nitrogen, and lead. The MCL for arsenic is 0.01 milligrams per liter (mg/L), uranium is 0.03 mg/L, nitrate-nitrogen is 10 mg/L, lead is 15 micrograms per liter (µg/L), and the recommended limit for radon is 4,000 picocuries per liter of air (pCi/L) (United States Environmental Protection Agency, 2021). However, these laws and standards are not applicable to private wells (United States Environmental Protection Agency, 2022c).

Private drinking water wells are vulnerable to chemical contamination as they are often located close to contamination sources, improperly constructed, and draw water from shallow, unconfined aquifers susceptible to contamination from naturally occurring sources or anthropogenic activities. Anthropogenic activities and sources that cause private well water contamination include farming, fertilizer use, mining, burning fossil fuels, plumbing, and industrial discharge. Naturally occurring sources that cause private well water contamination include soil, groundwater, and geology of rocks (United States Environmental Protection Agency, 2022a). As a result of laws and standards not applying to private wells and the various

vulnerabilities private wells endure, many individuals who rely on private wells as their drinking water source can have an abundance of chemical contaminants go undetected in their private well water, making it unsafe to drink. The lack of detection of these chemical contaminants in private well water can cause a plethora of adverse health outcomes in people that consume high levels of these contaminants, such as acute and chronic toxicity, liver, kidney, and intestinal damage, anemia, and cancer.

To increase private well water testing among Georgians, in the late 1990s, the University of Georgia's Extension program, which comprises the Agricultural and Environmental Services Laboratories (AESL), provided private well water testing of chemical contaminants upon the request of residents in Georgia (University of Georgia, n.d.). Since implementing the University of Georgia's Extension program, the AESL has offered basic physico-chemical water tests and an expanded list of chemicals for water tests. The basic tests include acidity (pH) and Hardness, Phosphorus (P), Potassium (K), Calcium (Ca), Aluminum (Al), Boron (B), Chromium (Cr), Copper (Cu), Iron (Fe), Magnesium (Mg), Manganese (Mn), Molybdenum (Mo), Nickel (Ni), Silica (SiO_2), Sodium (Na) and Zinc (Zn) in well water samples (University of Georgia, n.d.). The expanded water tests for basic contaminants as well as anions such as Chloride (Cl), Fluoride (F), Nitrate-Nitrogen (NO_3-N), Phosphate (PO_4), Sulfate (SO_4), Arsenic (As), Lead (Pb), Radon (Rn), Uranium (U), soluble salts, and alkalinity (University of Georgia, n.d.). As a result of these tests being offered to the public, the University of Georgia's Extension program has been able to track private well water quality in Georgia, especially for the chemical contaminants arsenic, uranium, radon, nitrate-nitrogen, and lead.

According to Clarke and McConnell, Georgia's geology consists of vastly different geological regions containing unique minerals, rock types, and landforms relative to each other

that can influence private well water quality (Clarke & McConnell, 1986). These geological regions in Georgia are classified into five distinct physiographic provinces: the Appalachian Plateau, Blue Ridge, Coastal Plain, Piedmont, and Valley and Ridge. Although anthropogenic activities and sources such as fertilizer use, mining, plumbing, and the combustion of fossil fuels can influence human environmental exposures to elevated concentrations of chemical contaminants in private well water supplies, the diverse geology in Georgia's physiographic provinces can influence these exposures as well, which can significantly differ from province to province (Clarke & McConnell, 1986). For instance, in each physiographic province in Georgia, there are specific types of aquifers or underground rocks that hold groundwater that contain different types of minerals and soils that influence the type and concentration levels of chemical contaminants that permeate into the ground and well water (Clarke & McConnell, 1986). Given that different geological strata in each physiographic province can influence the concentration levels of specific chemical contaminants in ground and well water, there is a need for a better understanding of the association between the physiographic provinces and concentrations of arsenic, uranium, radon, nitrate-nitrogen, and lead above the federal MCL in private well water. Therefore, this study aimed to examine the distribution of arsenic, uranium, radon, nitrate-nitrogen, and lead concentrations above the federal MCL in private well water and examine an association of contamination with physiographic provinces in Georgia specifically by utilizing private well water data collected by the University of Georgia's AESL.

2. Methods

2.1. Data sources and data collection

The data used in this study were obtained from the University of Georgia's AESL and the United States Geological Survey. The University of Georgia's AESL performs analyses of feeds,

forages, foods, feed ingredients, natural waters, and industrial wastewaters for those consumers who want these items tested (University of Georgia, n.d.). The United States Geological Survey provides scientific information that describes the earth pertaining to its water, energy, and mineral resources (United States Geological Survey, 2004). The analysis completed was identified as non-human subjects research by the Institutional Review Board (IRB) at Georgia State University (Protocol H22484).

Data from the University of Georgia's AESL were collected from samples of private well water provided by residents of Georgia who requested to have their samples tested for chemical contaminants between January 2010 and March 2022. The samples were tested for concentration levels of arsenic, uranium, radon, nitrate-nitrogen, and lead in private wells, used standard field protocols, and were analyzed by state-certified labs using approved testing techniques (University of Georgia, n.d.). Geospatial and temporal information, such as the date samples were tested and the city and county the samples came from, were collected. Data from the United States Geological Survey were collected from Fenneman's "Physical Divisions of the United States," which is based on eight major divisions, 25 provinces, and 86 sections representing distinctive areas having common topography, rock types and structure, and geologic and geomorphic history originally published on January 1, 1946, (United States Geological Survey, 2004).

2.2. Data analysis

2.2.1 Data cleaning, missing data, and outliers

Data from private well water samples were used to perform descriptive statistics to study the distribution of arsenic, uranium, radon, nitrate-nitrogen, and lead concentrations above the federal MCL in Georgia. Also, data from private well water samples were used to perform a Chi-

square test of Independence to assess if an association exists between the physiographic provinces and proportion of arsenic, uranium, radon, nitrate-nitrogen, and lead concentrations detected in private well water samples above the federal MCL in which the sample was collected. The county was filled in for samples with missing county information if the sample listed the city. Samples that were missing the city and county in which the sample was collected were excluded from the analysis. Each sample was matched with the physiographic province in which the county was located. Negligible values or concentrations of arsenic, uranium, radon, nitrate-nitrogen, and lead that were undetectable by the water sampling test were reported as 0.0009 mg/L for arsenic, 4.99 µg/L for lead, 0.0049 mg/L for uranium, and 0.049 mg/L for nitrate-nitrogen for statistical analysis. Extreme outliers were reviewed for each contaminant and removed for statistical analysis. The concentrations of arsenic, uranium, radon, nitrate-nitrogen, and lead detected in each water sample were dichotomized into "exceeding the Federal MCL or yes" or "not exceeding the federal MCL or no."

2.2.2 Analyses

The univariate analyses included descriptive statistics to study the distribution of arsenic, uranium, radon, nitrate-nitrogen, and lead concentrations above the federal MCL in Georgia. Descriptive statistics, such as the mean, standard deviation, lower quartile, upper quartile, median, minimum value, and maximum value, were calculated to demonstrate the variability of arsenic, uranium, radon, nitrate-nitrogen, and lead concentrations in each physiographic province. To test for bivariate associations between the physiographic provinces and the proportion of arsenic, uranium, radon, nitrate-nitrogen, and lead concentrations detected in private well water samples above the federal MCL, cross-tabulation with the chi-squared (χ^2) option was conducted. Phi (φ) was used to measure the strength of association between the two

categorical variables with statistically significant results, with Alpha set at $p < .05$. All analyses were conducted using SPSS Statistics (Version 27.0) software.

3. Results

3.1. Arsenic

Out of 26,686 private well water samples, a total of 2,671 samples were tested for arsenic contamination by the University of Georgia's Extension Program in Georgia during 2010-2022. As shown in Table 1, out of all private well water samples (N= 2,671) tested for arsenic contamination in each physiographic province, 19 private well water samples were from Valley and Ridge, 92 private well water samples were from Blue Ridge, 1,051 private well water samples were from Piedmont, and 1,509 private well water samples were from Coastal Plain.

Table 1.

The total number of private well water samples tested for arsenic contamination by the University of Georgia's Extension Program in each physiographic province in Georgia during 2010-2022.

Physiographic Province	N	Percent
Valley and Ridge	19	0.7
Blue Ridge	92	3.4
Piedmont	1051	39.4
Coastal Plain	1509	56.5
Total	2671	100.0

Out of 2,671 private well water samples tested for arsenic, 2,144 (80.3%) of samples were below the detection limit (<.001 mg/L). As shown in Table 2, descriptive statistics indicates

that among private well water samples tested for arsenic contamination, the mean arsenic concentration in Coastal Plain (*M* = .0038 mg/L, *SD* = .0074) was higher compared to other physiographic provinces. Out of all private well water samples tested for arsenic contamination, Coastal Plain had the highest maximum value of arsenic concentration (.1224 mg/L) compared to other physiographic provinces. Twenty-five percent of private well water samples tested for arsenic had concentrations that fell below .0009 mg/L in all physiographic provinces. Seventy-five percent of private well water samples tested for arsenic had concentrations that fell below .0009 mg/L in Blue Ridge and Piedmont, .005 mg/L in Valley and Ridge, and .0053 mg/L in Coastal Plain. All physiographic provinces had median arsenic concentrations of .0009 mg/L.

Table 2.

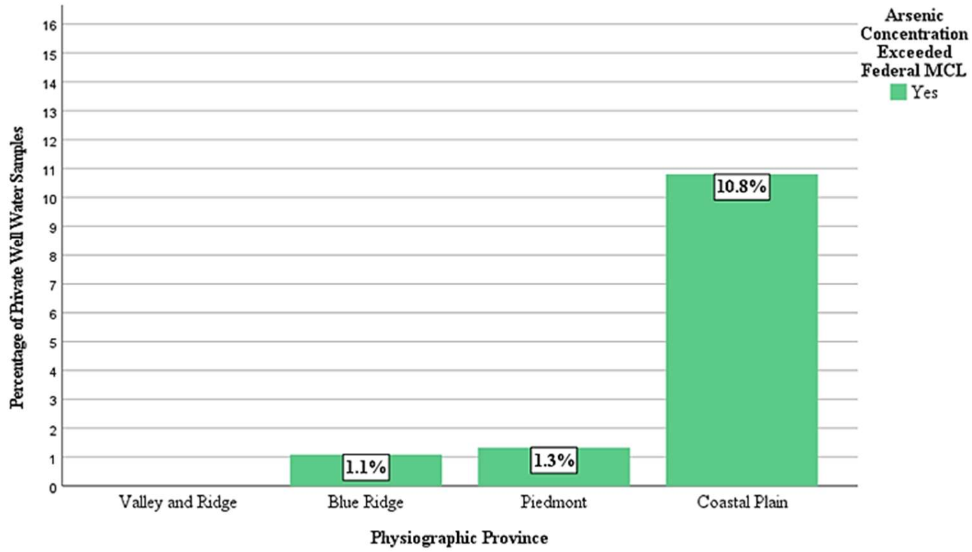
Descriptive statistics in mg/L of arsenic concentrations found in private well water samples in each physiographic province in Georgia during 2010-2022.

Physiographic Province	*M*	*SD*	*Minimum*	*Lower Quartile*	*Median*	*Upper Quartile*	*Maximum*
Valley and Ridge	.0026	.0026	.0009	.0009	.0009	.0050	.0080
Blue Ridge	.0011	.0013	.0009	.0009	.0009	.0009	.0117
Piedmont	.0015	.0021	.0001	.0009	.0009	.0009	.0281
Coastal Plain	.0038	.0074	.0000	.0009	.0009	.0053	.1224

A chi-square test of independence was performed to ascertain whether an association existed between physiographic provinces (Valley and Ridge, Blue Ridge, Piedmont, and Coastal Plain) and the proportion of private well water samples containing arsenic concentrations that exceeded the federal MCL.

Figure 4.

The percentage of private well water samples containing arsenic concentrations exceeding or not exceeding the federal MCL in each physiographic province.



As seen in Figure 4, Coastal Plain (10.8% of private well water samples with arsenic concentrations exceeding the MCL/Yes) had more private well water samples with arsenic concentrations exceeding the federal MCL compared to the other physiographic provinces (between 0% and 1.33%). There was a statistically significant association between the physiographic province and the proportion of private well water samples containing arsenic concentrations exceeding the federal MCL in the Coastal Plain, $\chi^2(3) = 95.53$, $p = <.001$. However, the expected count for one cell was less than five. There was a weak association between the physiographic province and the proportion of private water samples containing arsenic concentrations that exceeded the federal MCL, $\varphi = 0.189$, $p = <.001$.

3.2. Lead

Out of 26,686 private well water samples, a total of 7,562 private well water samples were tested for lead contamination by the University of Georgia's Extension Program in Georgia

during 2010-2022. As shown in Table 3, out of all private well water samples (N= 7,562) tested for lead contamination in each physiographic province, two private well water samples were from Appalachian Plateau, 104 private well water samples were from Valley and Ridge, 519 private well water samples were from Blue Ridge, 4,534 private well water samples were from Piedmont, and 2,403 private well water samples were from Coastal Plain.

Table 3.

The total number of private well water samples tested for lead contamination by the University of Georgia's Extension Program in each physiographic province in Georgia during 2010-2022.

Physiographic Province	N	Percent
Appalachian Plateau	2	0.1
Valley and Ridge	104	1.4
Blue Ridge	519	6.8
Piedmont	4534	59.9
Coastal Plain	2403	31.8
Total	7562	100.0

Out of 7,562 private well water samples tested for lead, 7,204 (95.3%) of samples were below the detection limit (<5.0 µg/L). Lead contained one extreme outlier with a value of 8598.00 µg/L, which was excluded from the analysis. As shown in Table 4, descriptive statistics indicates that among private well water samples tested for lead contamination, the mean lead concentration in Appalachian Plateau (M = 7.40 µg/L, SD = 3.40) was higher compared to other physiographic provinces. Out of all private well water samples tested for lead contamination, Coastal Plain had the highest maximum value of lead concentration (646.00 µg/L) compared to

other physiographic provinces. Twenty-five percent of private well water samples tested for lead had concentrations that fell below 4.99 µg/L in all physiographic provinces. Seventy-five percent of private well water samples tested for lead had concentrations that fell below 4.99 µg/L in Valley and Ridge, 7.60 µg/L in Blue Ridge, 6.40 µg/L in Piedmont, and 5.56 µg/L in Coastal Plain. All physiographic provinces had median lead concentrations of 4.99 µg/L except for Appalachian Plateau (7.40 µg/L).

Table 4.

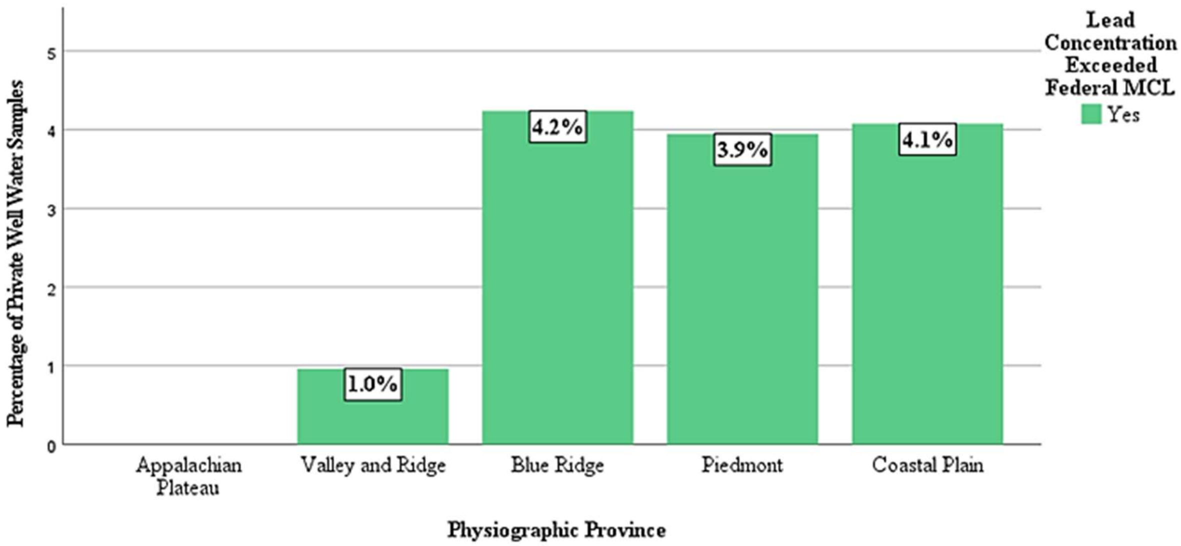
Descriptive statistics in µg/L of lead concentrations found in private well water samples in each physiographic province in Georgia during 2010-2022.

Physiographic Province	*M*	*SD*	*Minimum*	*Lower Quartile*	*Median*	*Upper Quartile*	*Maximum*
Appalachian Plateau	7.40	3.40	4.99	4.99	7.40	-	9.80
Valley and Ridge	6.20	10.43	4.99	4.99	4.99	4.99	111.00
Blue Ridge	6.64	7.74	1.00	4.99	4.99	7.60	95.30
Piedmont	6.86	17.28	.60	4.99	4.99	6.40	548.00
Coastal Plain	7.30	19.61	.60	4.99	4.99	5.56	646.00

A chi-square test of independence was performed to ascertain whether an association existed between physiographic provinces (Appalachian Plateau, Valley and Ridge, Blue Ridge, Piedmont, and Coastal Plain) and the proportion of private well water samples containing lead concentrations that exceeded the federal MCL.

Figure 5.

The percentage of private well water samples containing lead concentrations exceeding or not exceeding the federal MCL in each physiographic province



As seen in Figure 5, Blue Ridge (4.2% of private well water samples with lead concentrations exceeding the MCL/Yes) had more private well water samples with lead concentrations exceeding the federal MCL compared to the other physiographic provinces (between 0% and 4.1%). There was no statistically significant association between the physiographic province and the proportion of private well water samples containing lead concentrations exceeding the federal MCL, $\chi^2(4) = 2.731$, $p = .604$. However, the expected count for three cells was less than five.

3.3. Nitrate-nitrogen

Out of 26,686 private well water samples, a total of 14,384 private well water samples were tested for nitrate-nitrogen contamination by the University of Georgia's Extension Program in Georgia during 2010-2022. As shown in Table 5, out of all private well water samples (N=14,384) tested for nitrate-nitrogen contamination in each physiographic province, five private

well water samples were from Appalachian Plateau, 220 private well water samples were from Valley and Ridge, 720 private well water samples were from Blue Ridge, 8,959 private well water samples were from Piedmont, and 4,480 private well water samples were from Coastal Plain.

Table 5.

The total number of private well water samples tested for nitrate-nitrogen contamination by the University of Georgia's Extension Program in each physiographic province in Georgia during 2010-2022.

Physiographic Province	N	Percent
Appalachian Plateau	5	0.1
Valley and Ridge	220	1.5
Blue Ridge	720	5.0
Piedmont	8959	62.3
Coastal Plain	4480	31.1
Total	14384	100.0

Out of 14,384 private well water samples tested for nitrate-nitrogen, 14,292 (99.4 %) of samples were below the detection limit (<.05 mg/L). Nitrate-nitrogen contained four extreme outliers with values between 4069.92 and 4312.92 mg/L, which were excluded from the analysis. As shown in Table 6, descriptive statistics indicates that among private well water samples tested for nitrate-nitrogen contamination, the mean nitrate-nitrogen concentration in Piedmont (M = 1.739 mg/L, SD = 19.811) was higher compared to other physiographic provinces. Out of all private well water samples tested for nitrate-nitrogen contamination, Piedmont had the highest

maximum value of nitrate-nitrogen concentration (1011.870 mg/L) compared to other physiographic provinces. Twenty-five percent of private well water samples tested for nitrate-nitrogen had concentrations that fell below .049 mg/L in all physiographic provinces. Seventy-five percent of private well water samples tested for nitrate-nitrogen had concentrations that fell below .930 mg/L in Appalachian Plateau, .638 mg/L in Valley and Ridge, .188 mg/L in Blue Ridge, 1.070 mg/L in Piedmont, and .730 mg/L in Coastal Plain. Piedmont had the highest median nitrate-nitrogen concentration (.320 mg/L) while the other physiographic provinces had lower median nitrate-nitrogen concentrations (between .049-.270 mg/L).

Table 6.

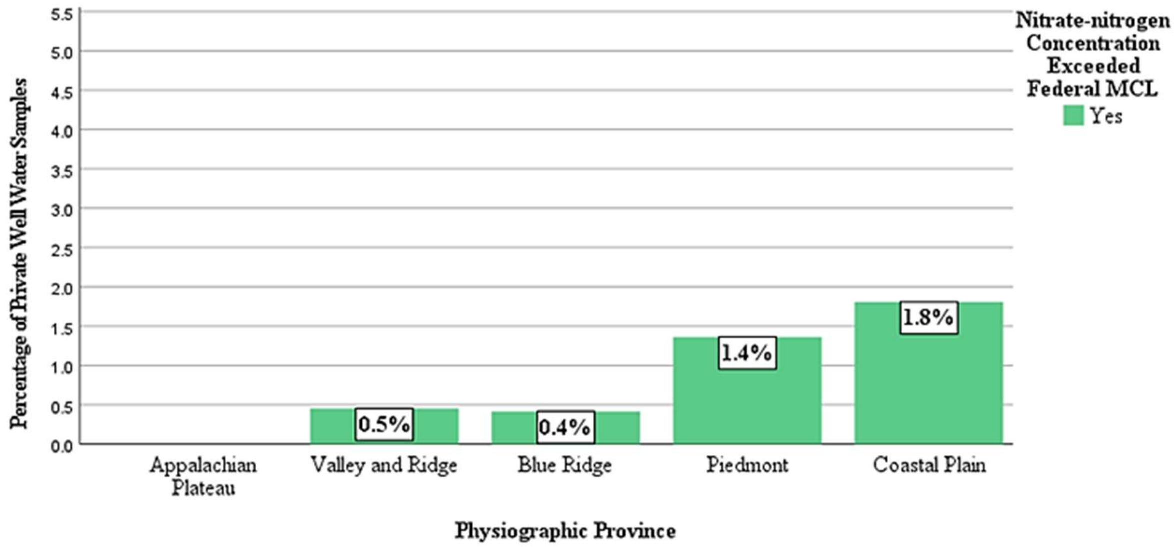
Descriptive statistics in mg/L of nitrate-nitrogen concentrations found in private well water samples in each physiographic province in Georgia during 2010-2022.

Physiographic Province	*M*	*SD*	*Minimum*	*Lower Quartile*	*Median*	*Upper Quartile*	*Maximum*
Appalachian Plateau	.446	.461	.049	.049	.270	.930	1.060
Valley and Ridge	.564	1.212	.049	.049	.210	.638	12.330
Blue Ridge	.289	1.058	.020	.049	.049	.188	19.590
Piedmont	1.739	19.811	.020	.049	.320	1.070	1011.870
Coastal Plain	1.071	3.271	.020	.049	.050	.730	55.090

A chi-square test of independence was performed to ascertain whether an association existed between physiographic provinces (Appalachian Plateau, Valley and Ridge, Blue Ridge, Piedmont, and Coastal Plain) and the proportion of private well water samples containing nitrate-nitrogen concentrations that exceeded the federal MCL.

Figure 6.

The percentage of private well water samples containing nitrate-nitrogen concentrations exceeding or not exceeding the federal MCL in each physiographic province.



As seen in Figure 6, Coastal Plain (1.8% of private well water samples with nitrate-nitrogen concentrations exceeding the MCL/Yes) had more private well water samples with nitrate-nitrogen concentrations exceeding the federal MCL compared to the other physiographic provinces (between 0% and 1.4%). There was a statistically significant association between the physiographic provinces and the proportion of private well water samples containing nitrate-nitrogen concentrations exceeding the federal MCL in the Coastal Plain, $\chi^2(4) = 11.56$, $p = .021$. However, three cells had an expected count of less than five. There was a weak association between the physiographic province and the proportion of private water samples containing nitrate-nitrogen concentrations that exceeded the federal MCL, $\varphi = 0.028$, $p = .027$.

3.4. Radon

Out of 26,686 private well water samples, a total of 589 private well water samples were tested for radon contamination by the University of Georgia's Extension Program in Georgia

during 2015-2022. As shown in Table 7, out of all private well water samples (N=589) tested for radon contamination in each physiographic province, 12 private well water samples were from Valley and Ridge, 134 private well water samples were from Blue Ridge, 420 private well water samples were from Piedmont, and 23 private well water samples were from Coastal Plain.

Table 7.

The total number of private well water samples tested for radon contamination by the University of Georgia's Extension Program in each physiographic province in Georgia during 2015-2022.

Physiographic Province	N	Percent
Valley and Ridge	12	2.0
Blue Ridge	134	22.8
Piedmont	420	71.3
Coastal Plain	23	3.9
Total	589	100.0

Radon contained six extreme outliers with values between 101590.6 and 145498.6 pCi/L, which were excluded from the analysis. As shown in Table 8, descriptive statistics indicates that among private well water samples tested for radon contamination, the mean radon concentration in Piedmont (M = 4362.50 pCi/L, SD = 13025.88) was higher compared to other physiographic provinces. Out of all private well water samples tested for radon contamination, Piedmont had the highest maximum value of radon concentration (91357.30 pCi/L) compared to other physiographic provinces. Twenty-five percent of private well water samples tested for arsenic had concentrations that fell below 130.35 pCi/L in Valley and Ridge, 651.68 pCi/L in Blue Ridge, 309.08 pCi/L in Piedmont, and 171.20 pCi/L in Coastal Plain. Seventy-five percent of

private well water samples tested for arsenic had concentrations that fell below 887.00 pCi/L in Valley and Ridge, 17816.70 pCi/L in Blue Ridge, 91357.30 pCi/L in Piedmont, and 5714.50 pCi/L in Coastal Plain. Blue Ridge had the highest median radon concentration (1659.45 pCi/L) while the other physiographic provinces had lower median radon concentrations (between 370.05-1015.80 pCi/L).

Table 8.

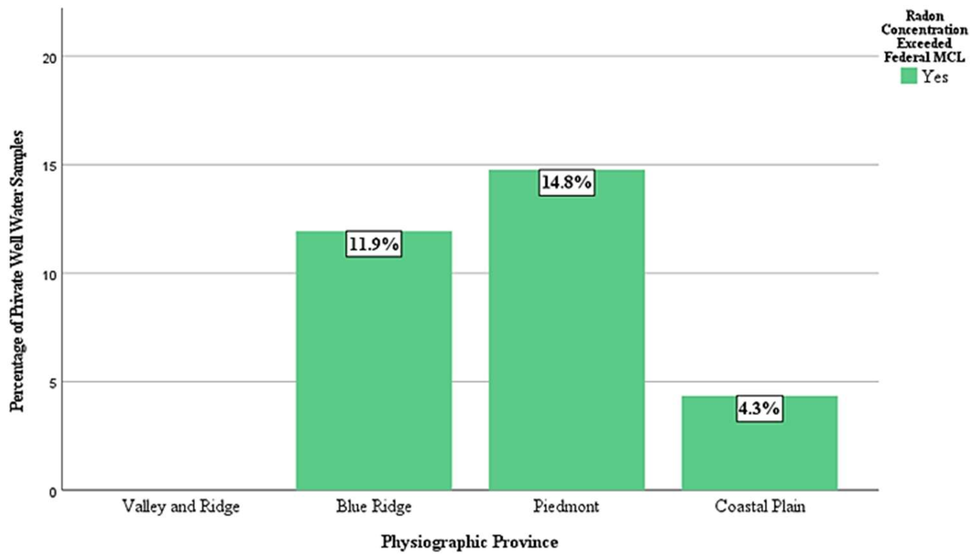
Descriptive statistics in pCi/L of radon concentrations found in private well water samples in each physiographic province in Georgia during 2015-2022.

Physiographic Province	*M*	*SD*	*Minimum*	*Lower Quartile*	*Median*	*Upper Quartile*	*Maximum*
Valley and Ridge	540.63	543.08	59.80	130.35	370.05	887.00	1667.00
Blue Ridge	1987.90	2027.87	46.00	651.68	1659.45	2871.85	17816.70
Piedmont	4362.50	13025.88	.0	309.08	1015.80	2460.75	91357.30
Coastal Plain	919.54	1277.75	29.6	171.20	390.70	1625.00	5714.50

A chi-square test of independence was performed to ascertain whether an association existed between physiographic provinces (Valley and Ridge, Blue Ridge, Piedmont, and Coastal Plain) and the proportion of private well water samples containing radon concentrations that exceeded the federal MCL.

Figure 7.

The percentage of private well water samples containing radon concentrations exceeding or not exceeding the federal MCL in each physiographic province.



As seen in Figure 7, Piedmont (14.8% of private well water samples with radon concentrations exceeding the MCL/Yes) had more private well water samples with radon concentrations exceeding the federal MCL compared to the other physiographic provinces (between 0% and 11.9%). There was no statistically significant association between the physiographic provinces and the proportion of private well water samples containing radon concentrations exceeding the federal MCL, $\chi^2(3) = 4.395$, $p = .222$. However, two cells had an expected count of less than five.

3.5. Uranium

Out of 26,686 private well water samples, a total of 1,480 private well water samples were tested for uranium contamination in Georgia by the University of Georgia's Extension Program during 2010-2022. As shown in Table 9, out of all private well water samples (N=1,480) tested for uranium contamination in each physiographic province, five private well

water samples were from Valley and Ridge, 13 private well water samples were from Blue Ridge, 1,307 private well water samples were from Piedmont, and 155 private well water samples were from Coastal Plain.

Table 9.

The total number of private well water samples tested for uranium contamination by the University of Georgia's Extension Program in each physiographic province in Georgia during 2010-2022.

Physiographic Province	N	Percent
Valley and Ridge	5	0.3
Blue Ridge	13	0.9
Piedmont	1307	88.3
Coastal Plain	155	10.5
Total	1480	100.0

Out of 1,480 private well water samples tested for uranium, 1,416 (95.7%) of samples were below the detection limit (<.005 mg/L). Uranium contained one extreme outlier with a value of 6.2973 mg/L, which was excluded from the analysis. As shown in Table 10, descriptive statistics indicates that among private well water samples tested for uranium contamination, the mean uranium concentration in Piedmont (M = .0174 mg/L, SD = .0840) was higher compared to other physiographic provinces. Out of all private well water samples tested for uranium contamination, Piedmont had the highest maximum value of uranium concentration (1.549 mg/L) compared to other physiographic provinces. Twenty-five percent of private well water samples tested for uranium had concentrations that fell below .0049 mg/L in all physiographic

provinces. Seventy-five percent of private well water samples tested for uranium had concentrations that fell below .0049 mg/L in all physiographic provinces. All physiographic provinces had median uranium concentrations of .0049 mg/L.

Table 10.

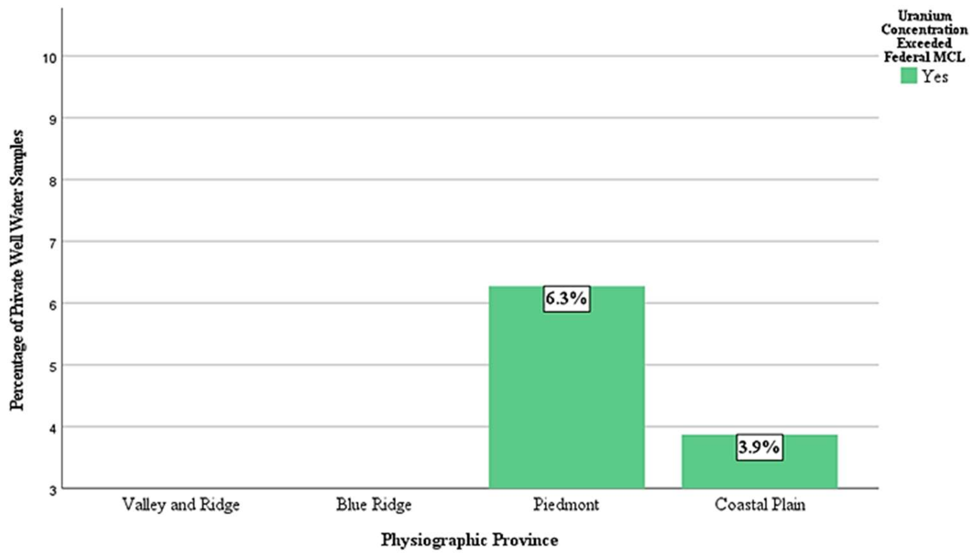
Descriptive statistics in mg/L of uranium concentrations found in private well water samples in each physiographic province in Georgia during 2010-2022.

Physiographic Province	*M*	*SD*	*Minimum*	*Lower Quartile*	*Median*	*Upper Quartile*	*Maximum*
Valley and Ridge	.0049	.0000	.0049	.0049	.0049	.0049	.0049
Blue Ridge	.0054	.0017	.0049	.0049	.0049	.0049	.0112
Piedmont	.0174	.0840	.0027	.0049	.0049	.0049	1.549
Coastal Plain	.0076	.0152	.0049	.0049	.0049	.0049	.1741

A chi-square test of independence was performed to ascertain whether an association existed between physiographic provinces (Valley and Ridge, Blue Ridge, Piedmont, and Coastal Plain) and the proportion of private well water samples containing uranium concentrations that exceeded the federal MCL.

Figure 8.

The percentage of private well water samples containing uranium concentrations exceeding or not exceeding the federal MCL in each physiographic province.



As seen in Figure 8, Piedmont (6.3% of private well water samples with uranium concentrations exceeding the MCL/Yes) had more private well water samples with uranium concentrations exceeding the federal compared to the other physiographic provinces (between 0% and 3.9%). There was no statistically significant association between the physiographic provinces and the proportion of private well water samples containing uranium concentrations exceeding the federal MCL, $\chi^2(3) = 2.583$, $p = .461$. However, three cells had an expected count of less than five.

4. Discussion

This study examined private well water data from the University of Georgia's AESL to study the distribution of arsenic, uranium, radon, nitrate-nitrogen, and lead concentrations above the federal MCL and its association with physiographic provinces in Georgia. To date, there are relatively few studies examining private well water samples in Georgia, and this is the first study

in Georgia to investigate the association between private well water exceeding the federal MCL for arsenic, uranium, radon, nitrate-nitrogen, and lead and the physiographic province in which the sample was taken. Overall, samples tested for arsenic and nitrate-nitrogen with concentrations exceeding the MCL appeared more often in the Coastal Plain province. Samples tested for lead with concentrations exceeding the MCL appeared more often in the Blue Ridge province. Samples tested for radon and uranium with concentrations exceeding the MCL appeared more often in the Piedmont province. There were no statistically significant associations between private well water samples with exceeding concentrations of uranium, radon, and lead above the federal MCL and the physiographic province in which the sample was taken. However, the study revealed that there were statistically significant associations between the proportion of private well water samples that contained arsenic and nitrate-nitrogen exceeding the federal MCL and the Coastal Plain province. Therefore, this study suggests that the distribution of exceeding concentrations of arsenic and nitrate-nitrogen above the federal MCL in private well water is significantly influenced by the physiographic province in which the private well is located.

4.1. Associations between a physiographic provinces' geology and water quality in Georgia

According to Clarke and McConnell, Georgia's geology consists of vastly different geological regions containing unique minerals, rock types, and landforms relative to each other that can influence private well water quality. Although anthropogenic activities and sources such as fertilizer use, mining, plumbing, and the combustion of fossil fuels can influence human environmental exposures to elevated concentrations of chemical contaminants in private well water supplies, the diverse geology in Georgia's physiographic provinces can influence these exposures as well, which can significantly differ from province to province (Clarke &

McConnell, 1986). For instance, Clarke and McConnell suggested that compared to the Piedmont and Blue Ridge provinces, the Valley and Ridge and Coastal Plain provinces have loose soil that allows chemically contaminated water to permeate into the ground easily and replenish the aquifers and wells; hence, the potential for chemical contamination is more significant (Clarke & McConnell, 1986).

Moreover, Clarke and McConnell discovered that in each physiographic province in Georgia, different aquifers vary in natural groundwater quality. They are linked to different geological strata, influencing the type and concentration of chemical contaminants in well water (Clarke & McConnell, 1986). For instance, in the Coastal Plain, the aquifers contain limestone and dolomite, which naturally contain arsenic. Similarly, Swain et al. suggested that there is an association between the quality of ground and well water and the geological traits of the physiographic provinces in Georgia due to the residence time of water within the aquifer, depth of circulation, and mineral composition of the rock matrix (Swain et al., 1991).

Furthermore, given that the Coastal Plain province in Georgia is predominantly rural and participates in many agricultural activities such as farming and fertilizer use, nitrate-nitrogen contamination of wells is likely. When it rains near agricultural sites containing wells, nitrate-nitrogen run-off can get into wells, primarily if heavy rainfall occurs. Since the Coastal Plain has loose soil that allows chemically contaminated water to easily permeate into the ground and replenish the aquifers and wells, finding statistically significant associations between the proportion of nitrate-nitrogen that exceeded the federal MCL in the Coastal Plain was expected.

Additionally, in the Coastal Plain, the aquifers contain limestone and dolomite, which naturally contain arsenic (Clarke & McConnell, 1986). These rocks and minerals can make up the aquifers that replenish the wells, which can naturally contaminate well water with inorganic

arsenic. In well water, inorganic arsenic usually occurs in two forms: trivalent arsenic (As+3, or arsenite), pentavalent arsenic (As+5, or arsenate), or both (Pure Water Occasional, n.d.). Trivalent arsenic is arsenic with three fewer electrons than protons, giving it a plus three positive charge; pentavalent arsenic is arsenic with five fewer electrons than protons, giving it a plus five positive charge (Dartmouth, n.d.). Depending on the physico-chemical properties of well water, such as acidity (pH), oxygen, iron, and other molecules that may be present, these two forms can be readily converted back and forth in well water (Dartmouth, n.d.). Although both forms can occur in well water, trivalent arsenic is difficult to remove from water and may pose challenges to remediation methods (Pure Water Occasional, n.d.). Given that the Coastal Plain contains rocks and minerals that contain naturally occurring arsenic, finding statistically significant associations between the proportion of arsenic that exceeded the federal MCL in the Coastal Plain was expected.

Moreover, lead rarely occurs naturally in water but can be present in bedrock wells (University of Massachusetts Amherst, 2007). In wells constructed in granitic (amphibole, potassium feldspar, quartz, and sodium feldspar) rock formations, elevated lead concentrations have been detected (University of Massachusetts Amherst, 2007). However, nearly all lead in drinking water comes from anthropogenic sources such as water that stands idle in corroded pipes, plumbing, and components in well water systems that contain lead (Minnesota Department of Health, 2019). Given that anthropogenic sources predominantly contaminates wells, finding lack of associations between the proportion of lead that exceeded the federal MCL and physiographic provinces were expected. Lead contamination of water can occur in wells regardless of the physiographic province the well may be located.

4.2. Ground and well water quality monitoring in Georgia

Despite the premises described above of how the geology of a physiographic province introduces chemical contaminants into the ground and well water supplies above the federal MCL in Georgia, previous studies did not provide data that examined an association between the proportion of elevated concentrations of arsenic, uranium, radon, nitrate-nitrogen, and lead found in private well water supplies in Georgia and the physiographic provinces in which the well was located. A study by Swain et al. described the relationship between geology and chemical contamination of groundwater regarding its hardness and concentration of calcium, iron, magnesium, and dissolved solids (Swain et al., 1991). Studies by Tyson et al., Bush et al., and Leeth et al. described the average nitrate-nitrogen concentrations for each physiographic province, while Tyson et al. and Bush et al. described a potential association between nitrate-nitrogen concentrations and shallow and deep wells (Bush et al., 1997; Tyson et al., 1995). Leeth et al. examined if nitrate-nitrogen concentrations in wells for each major aquifer in Georgia were more or less than what was recorded in previous years (Leeth et al., 2003). Lastly, a study by Sonon et al. provided a descriptive analysis of the averages of chemical contaminant concentrations found in private well water samples in the major physiographic provinces of Georgia that exceeded federal MCL (Sonon et al., 2005).

Furthermore, previous studies that analyzed ground and private well water samples used methodologies that calculated the median and average concentrations of specific chemical contaminants. However, this method does not provide enough evidence to ascertain that specific chemical contaminants found in private well water that exceed the MCL are associated with the physiographic province in which it was taken, given the variability of the concentrations found in each water sample. Therefore, using improved methodologies such as the statistical testing used

in this study provided the best evidence of an association between specific chemical contaminants that exceeded the federal MCL in private well water and the physiographic province in which the sample was taken. Moreover, past studies on the quality of ground and private well water in Georgia have mainly focused on detecting elevated concentrations of nitrate-nitrogen above the federal MCL in the major physiographic provinces and aquifers in Georgia. However, based on the results of this study, the chemical contaminants radon, uranium, lead, and arsenic are also found in increased concentrations in Georgia's private well water supplies and are an emergent concern today.

4.3. Public health implications

The provision of safe drinking water is one of the most important public health achievements of the 20th century (Centers for Disease Control and Prevention, 2022). Water treatment methods for CWS have helped ensure access to healthy and safe water for millions of Americans. However, these water treatment methods do not apply to private well water owners who are responsible for their own water's health and safety. Consequently, numerous households that rely on private well water do not routinely test their well water as suggested by their local health departments, thus, missing the opportunity to monitor an abundance of chemical contaminants that can go undetected in their drinking water (Association of Public Health Laboratories, 2019). This study shows that well water can contain chemical contaminants exceeding the federal MCL. If most private well water owners in Georgia do not test their well water, they could potentially consume elevated levels of arsenic, radon, uranium, nitrate-nitrogen, and lead above the federal MCL, causing severe illness.

Research has shown that ingesting nitrate-nitrogen contaminated drinking water causes health effects such as increased heart rate, nausea, headaches, abdominal cramps, gastric

cancer, and congenital disabilities while pregnant (Minnesota Department of Health, n.d.; Skipton et al., 2013). Also, studies have shown that infants who drink water with high nitrate levels may develop a serious health condition called methemoglobinemia or “blue baby syndrome” (Washington State Department of Health, n.d.). Additionally, ingesting lead contaminated drinking water causes cardiovascular problems, decreased kidney function and reproductive problems in adults, reduced fetus growth, premature birth in pregnant women, anemia, slowed growth, and lower IQ in children (United States Environmental Protection Agency, 2022b). Ingesting arsenic contaminated drinking water causes nausea, vomiting, stomach pain, diarrhea, blindness, partial paralysis, and cancer of the bladder, lungs, skin, kidneys, liver, and prostate (United States Environmental Protection Agency, 2021). Ingesting uranium contaminated drinking water has been linked to kidney toxicity and an increased risk of cancer (Water Quality Association, n.d.). Lastly, ingesting radon contaminated drinking water has been linked to an increased risk of lung and stomach cancer (Kansas State University, n.d.)

4.4. Study strengths and limitations

This study had several strengths and limitations. This study's relatively high number of private well water samples provided enough data to test the association between the two categorical variables. The limitations of this study included using private well water sample data from a convenience sample. Given that the water samples were brought voluntarily, the proportion of wells covered in each physiographic province in Georgia is unknown. Another limitation was that the data used in this study did not indicate which samples were repeated from the same household. It is possible that one well may be represented several times during the time period. All samples were assumed to be individual private well water samples from different households, which could overestimate the proportion of private wells with concentrations of

arsenic, uranium, radon, nitrate-nitrogen, and lead above the federal MCL in each physiographic province.

5. Conclusion

The study findings provide further evidence that exceeding concentrations of arsenic, uranium, radon, nitrate-nitrogen, and lead above the federal MCL in private well water supplies may be influenced by the physiographic province in which a well is located. Although statistically significant associations were found for some chemical contaminants, future studies could fruitfully explore this issue further by first taking a simple random sample of private wells from a list of all wells in each physiographic province in Georgia. Secondly, testing the private well water samples from the list of randomly sampled wells for elevated concentrations of arsenic, uranium, radon, nitrate-nitrogen, and lead above the federal MCL. Thirdly, using statistical testing to test for potential associations between the proportion of private well water samples that contain chemical contaminants that exceed the federal MCL and the physiographic provinces in Georgia in which the sample was taken.

Furthermore, given that private well water owners are responsible for the safety of their water, results from this study can be used to inform private well water owners on the specific chemical contaminants that are likely to exceed the federal MCL in their well water, which can prevent adverse health outcomes. These results will help private well owners prioritize which chemical contaminants they should test for based on the physiographic province in which they reside. In addition, study findings could help allocate state tax dollars to local public health entities to educate and encourage the public on the importance of well water testing. Also, these state tax dollars could subsidize well water testing for private well owners once a year for chemical contaminants that pose the biggest threat of exceeding the federal MCL based on the

physiographic province in which they reside. Further, if any private well water tests for exceeding concentrations of a contaminant specific to the physiographic province, these state tax dollars could also help clean up the pollutant in their well water. Ultimately, elevated concentrations of arsenic, uranium, radon, nitrate-nitrogen, and lead can cause adverse conditions such as chronic toxicity, liver, kidney, and intestinal damage, anemia, and cancer that can impact health. Understanding the geological factors behind poor well water quality will promote public health initiatives that increase public awareness and provide opportunities to maintain healthy well water quality in Georgia.

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