Strontium in Drinking Water: Assessing Strontium as a Drinking Water Contaminant in Virginia Private Wells

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Approximately 80% of Virginians with private drinking water (PDW) sources are unaware of the quality of their drinking water. Strontium is a water quality contaminant gaining recognition at the federal level. At concentrations >1.5 mg/L, strontium substitutes calcium in the bones leading to bone density disorders (e.g. rickets). This is particularly problematic for children and individuals with low calcium and low protein diets. Because most Virginians do not know the quality of their PDW and since strontium poses a public health risk, this study investigates the sources of strontium in PDW in Virginia and identifies the areas and populations most vulnerable. Physical factors such as rock type, rock age, and fertilizer use have been linked to elevated strontium concentrations in drinking water. Meanwhile, social factors such as poverty, poor diet, and adolescence also increase social vulnerability to health impacts of strontium. Thus, this study identifies both physically and socially vulnerable regions in Virginia using water quality data from the Virginia Household Water Quality Program and statistical and spatial analyses conducted in RStudio 1.0.153 and ArcMap 10.5.1. Physical vulnerabilities were highest in the Ridge and Valley province where geologic formations with high strontium concentrations (e.g., limestone, dolomite, sandstone, and shale) are the dominant the aquifer rocks. The complex relationship between agricultural land use and strontium concentrations made it difficult to determine the impact of fertilizer use on strontium concentrations in PDW in Virginia. In general, the spatial distribution of social vulnerability factors was distinct from physical factors with the exception of food deserts. This study provides information and analysis to help residents of Virginia understand their risk of strontium exposure in PDW.

General Audience Abstract

There are 1.7 million residents in Virginia that rely on private drinking water supplies in their homes. Those individuals are responsible for knowing how often to test their water, what to test their water for, and how to treat their water, if needed, to achieve safe drinking standards. Unfortunately, approximately 80% of Virginians with private drinking water sources (e.g., wells, cisterns, and springs) do not know if their water is safe to drink. Strontium, an element closely related to calcium, is a contaminant that the federal government recognizes as dangerous because in high quantities (>1.5 mg/L of water) it can replace calcium in bones making them brittle (e.g. rickets). These health impacts are more extreme in children and individuals with low calcium and low protein diets. Since strontium poses a public health risk, this study identified areas and populations in Virginia that have higher chances of being exposed to strontium and higher chances of their health being impacted by high levels of strontium. Physical factors such as rock type, rock age, and fertilizer use have been linked to elevated strontium concentrations in drinking water, indicating various physical vulnerabilities. Meanwhile, social factors such as poverty, poor diet, and adolescence also increase social vulnerability to the health impacts of strontium. This paper investigates regions in Virginia that are likely to contain high strontium levels and thus potential health impacts from strontium. Statistical and spatial analyses of water quality data from Virginia Cooperative Extension's Virginia Household Water Quality Program combined with risk factor data identified vulnerable areas in Virginia. The highest chance of exposure was in counties near the western border of the state (e.g., Augusta, Fredrick, Highland, Montgomery, Shenandoah, and Wythe) due to the presence of limestone, dolomite, sandstone, and shale, all of which naturally contain high amounts of strontium. The land use data indicated that there were no strong patterns of strontium occurrence relative to fertilizer use. In general, the spatial distribution of social vulnerability factors was distinct from physical factors with the exception of food deserts occurring at high rates in the same areas as the samples with high strontium levels (e.g., Augusta, Fredrick, Highland, Montgomery, Shenandoah, and Wythe). The presence of food deserts prevents individuals from obtaining a high calcium and high protein diet, which makes them more vulnerable to the impacts of strontium. Overall, this study can help people in Virginia who are not on public water systems understand their risk of from being exposed to strontium.

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Table of Contents

List of Figures

List of Tables

List of Abbreviations

ARC – Appalachian Regional Commission

CCL – Contaminant Candidate List

CSV – Comma Separated Value

EPA – Environmental Protection Agency

GPS – Global Positioning System

HUNV – Housing Units without a Vehicle

NLCD – National Land Cover Dataset

PDW – Private Drinking Water

RHL – Recommended Health Limit

SNAP – Supplemental Nutrition Assistance Program

SDWA – Safe Drinking Water Act

UN – United Nations

USCB – United States Census Bureau

USDA – United States Department of Agriculture

USGS – United States Geologic Department

VAHWQP – Virginia Household Water Quality Program

1. Introduction

1.1 Problem Statement

Water is so vital to our lives that the United Nations (UN) formally acknowledged access to clean, safe drinking water as a human right (UN, 2010). The United States also recognizes its importance, and in 1974 enacted the Safe Drinking Water Act (SDWA) to protect public drinking water for the health of individuals and society as a whole (United Sates SDWA, 1974). Every five years the Environmental Protection Agency (EPA) is tasked with identifying contaminants to add to the SDWA. While the EPA protects public water, there is no federal agency that similarly protects private water supply systems. Over 20% of Virginians obtain drinking water from private sources (typically wells, but also springs and cisterns), and they are often unaware of the quality or safety of the water (Desimone, Mcmahon, & Rosen, 2015).

In 2008, strontium was added to the list of potential contaminants in drinking water (United Sates United States EPA, 2014; Health & Services, 2000). Strontium has been shown to be detrimental to human health and can be found in waters throughout the United States, which brought it to the attention of the EPA (United Sates United States EPA, 2014; Health & Services, 2000). Strontium is monitored in public drinking water systems, however there is no system in place to monitor strontium in private drinking water systems. Thus, there is a need for a program to monitor this potential contaminant.

Very few large-scale studies examine water quality in private water supply systems in the United States (Allevi et al., 2013; Benham, Ling, Ziegler, & Krometis, 2016; Clark et al., 2009; Desimone, Mcmahon, & Rosen, 2015; Johnson & Belitz, 2015, 2017; Pieper, Krometis, & Edwards, 2016; Pieper, Krometis, Gallagher, Benham, & Edwards, 2015; Pieper, Krometis, Benham, & Gallagher, 2016; Smith et al., 2014; VanDerwerker, Zhang, Ling, Benham, & Schreiber, 2018), even fewer examine strontium (Fontenot et al., 2013; Hildenbrand et al., 2016; Knobeloch, Gorski, Christenson, & Anderson, 2013), and none examine strontium in Virginia private water supply systems. A survey that investigates levels of strontium in drinking water throughout the state of Virginia offers first-of-its kind data and would allow residents to better understand potential health risks and respond appropriately to attenuate the risks. Furthermore, because this study focuses on strontium in private water supplies, it also provides critical information to a subset of the population that are unaware of their water quality (Benham et al., 2016). The need for investigating strontium in private drinking water supplies addresses the following research questions:

1. What is the level of strontium in private drinking water systems in Virginia?
2. What are the physical vulnerabilities to strontium contamination in private drinking water systems in Virginia?
3. What are the social vulnerabilities to strontium contamination in private drinking water systems in Virginia?

2. Literature Review

2.1 Water Quality Legislation

The United States Environmental Protection Agency (EPA) is tasked with enforcing the Safe Drinking Water Act (SDWA) of 1974 (Health & Services, 2000). The SDWA applies to water sources that have at least 15 service connections or serve 25 residents year-round (United Sates SDWA, 1974). Systems that meet SDWA requirements are considered public sources and an individual, corporation, company, association, partnership, or government agency is responsible for maintenance, testing, and treatment (United Sates SDWA, 1974). Currently the EPA SDWA mandates regulation of 88 contaminants including microorganisms, organic and inorganic chemicals, radionuclides, disinfectants, and disinfectant byproducts (United States United States EPA, 2014). The number of regulated contaminants continually increases because the Regulatory Determination Amendment to the SDWA calls for the Administrator of the EPA to suggest at least five contaminants be added to the Contaminant Candidate List (CCL) every five years (United Sates SDWA, 1974). The new contaminants are suggested in the Drinking Water CCL, and each contaminant must meet several conditions: proven to have an adverse health effect, known to occur in public water systems, and present a meaningful opportunity to reduce health risk (United States EPA, 2014). In 2008, strontium was added to the Third Drinking Water CCL (United States EPA, 2014). The EPA found that strontium meets all three of the requirements to be part of the SDWA (United States EPA, 2014), but as of April 11th, 2019 no final decision about strontium has been made. While the EPA monitors public water systems, there is no national system in place to regulate or monitor private systems. Additionally, there are no states that regulate regular testing of private water or standards for private drinking water (PDW) quality. In Virginia, newly constructed private wells are required to be tested, but state legislation dictates testing only one time and only for coliform organisms (Virginia Department of Health, 2019). Currently, Virginia has no statewide systems in place that monitor private drinking water quality.

2.2 Strontium

2.2.1 Natural Sources

Strontium is a naturally occurring alkaline earth metal element with an atomic number of 38 (Health & Services, 2000). There are four naturally-occurring stable isotopes of strontium, Sr-84, Sr-86, Sr-87, and Sr-88 (Health & Services, 2000). Strontium has more than 20 radioactive isotopes, but only one radioactive isotope Strontium-90, which is mainly created through above ground nuclear testing is abundant on Earth's surface (Health & Services, 2000; Watts & Howe, 2010). The naturally occurring isotopes of strontium mostly exist in the +2 oxidation state and are fluid mobile on Earth's surface, thus allowing them to be transported by and present in water (Watts & Howe, 2010). Naturally occurring strontium has an abundance of 0.02-0.03% in Earth's crust (Watts & Howe, 2010). Strontium is a major element in minerals such as Celestite ($SrSO_4$) and Strontianite ($SrCO_3$), and also occurs in minor and trace quantities in sedimentary rocks like slate, shale, limestone, sandstone, and coal (Health & Services, 2000; Watts & Howe, 2010). Strontium also occurs in calcite minerals in trace amounts (Wiegand, 2009). These geological sources of strontium should be considered when determining the sources of strontium in drinking water.

2.2.2 Anthropogenic Sources

Strontium also enters drinking water from anthropogenic sources. Strontium-90 is an isotope that can only occur as a result of human activities and is known to enter the environment as a result of nuclear fallout and to a lesser extent as a constituent in nuclear, medical, and industrial waste (Health & Services, 2000; Watts & Howe, 2010). Non-radioactive isotopes of strontium can also be found at high levels due to human activities. Three commonly used solid phosphate fertilizers (monoammonium phosphate, diammonium phosphate, and triple superphosphate) were shown to have elevated concentrations of strontium (Raven & Loeppert, 1997). Phosphate fertilizer use and production has been linked to elevated strontium levels in nearby water sources with up to 25% of dissolved strontium sourced from fertilizers (Böhlke & Horan, 2000; Hosono et al., 2007; Jiang, 2011; Volokh et al., 1990). Strontium is used in several industrial processes; in fact, 85% of strontium consumed in the United States is used to produce ceramic and glass products, primarily television faceplate glass (Watts & Howe, 2010). The abundance of strontium in anthropogenic sources suggests that these could be potential sources of contamination drinking water

2.2.3 Health Effects

The Agency for Toxic Substances and Disease Registry produced a Toxicological Profile for Strontium in April 2000 (Health & Services, 2000). The report comprehensively examines the health effects of exposure to strontium. The report found that strontium is not toxic to humans under standard environmental levels, listed at 0.5-1.5 mg Sr/L H_2O (Health & Services, 2000). However, when consumed in abnormally high levels, strontium can cause negative health effects, primarily a skeletal disorder called rickets (Health & Services, 2000). Strontium causes bone disorders after entering the bloodstream through the intestines (Health & Services, 2000). Once strontium is in the bloodstream, it mimics calcium and accumulates in and on bones (Health & Services, 2000). Children, especially infants, are vulnerable to strontium accumulation due to higher absorption rates and their growing bones allow strontium to take the place of calcium while bone mineral is being produced (Health & Services, 2000) Watts & Howe, 2010). Strontium is eliminated from the body through urine, feces, and sweat over long periods (Health &

Services, 2000). While high levels of ingested strontium cause bone disorders, impaired bone growth, and most notably rickets, the effects are mitigated by a diet that is high in calcium and protein by limiting the amount of strontium that is absorbed after ingestion (Health & Services, 2000; Watts & Howe, 2010).

Like naturally occurring strontium, radioactive strontium does not cause adverse health effects at low-level exposure over time. However, high levels of exposure can cause adverse health effects such as cancer (Health & Services, 2000). Leukemia, bone, nose, lung, and skin cancers are a result of damage to genetic material (DNA) in cells from exposure to radioactive isotopes like strontium (Health & Services, 2000). Strontium-90 emits beta particles that ionize cellular molecules, which results in disrupted cell functions and tissue damage (Health & Services, 2000).

2.2.4 Removal Process

Strontium may be removed from water using treatment techniques that are already widely available (Benham et al., 2016; O'Donnell, 2014). While traditional coagulation and filtration water treatment is not an effective method of removing strontium from drinking water, strontium can be removed from water sources using water softeners such as lime softeners or cation exchange filters (O'Donnell, 2014; O'Donnell et al., 2016)

2.3 Vulnerability to Strontium

2.3.1 Physical Vulnerability

Strontium can enter water through both natural and anthropogenic pathways. Anthropogenic sources of strontium include nuclear reactors and fertilizers (Health & Services, 2000). According to an analysis of 1997 Census of Agriculture for Virginia data, there are approximately 8.25 million acres of land used for agriculture in Virginia, which is about 33% of land acreage per county (Pease, 2009). The report found that there is a small decline in the amount of land used for agriculture (about 1% per year), but the rate of decline has been decreasing since the 1990s (Pease, 2009). Farmland is spread throughout all regions of Virginia with the smallest amount of acreage in the northeast region, which is also a region with high rates of urban land use (Pease, 2009). Many studies have investigated connections between fertilizer use and elevated strontium concentrations in nearby water sources (Hosono et al., 2007; Jiang, 2011; Volokh et al., 1990). These studies found that agriculture changes the isotope ratios and concentrations of strontium in both ground and surface waters with up to 25% of strontium coming from agricultural activities and the remaining 75% from source rocks (Hosono et al., 2007). A study conducted in Maryland watersheds showed strontium levels are related to the type, amount, history, and cumulative legacy of fertilizer use (Böhlke & Horan, 2000). However, agriculture is not the only anthropogenic source of strontium.

here are low levels of contamination across the USA, the majority of which resides in soils and slowly leaches into groundwater and vegetation (Health & Services, 2000). There are two nuclear reactors in the state of Virginia that are potential sources of strontium, but no above ground nuclear tests or nuclear accidents have occurred in the state, so there is low risk of exposure to high levels of Sr-90 in the study area (United States Department of Energy, 2017).

Aside from anthropogenic sources, natural sources of strontium include a variety of rock types (Health & Services, 2000). There are 25 physiographic provinces in the United States that are broadly defined by characteristic rock types, topography, structure, and shared geological history (Fenneman & Johnson, 1946). The Appalachian Plateau, Ridge and Valley, Blue Ridge, Piedmont, and Coastal Plain are the five provinces, shown in Figure 1, that occur in Virginia (Fenneman & Johnson, 1946). The Appalachian Plateau is known for shale, slate, and coal, which can all contribute to strontium in groundwater (Smith & Ellison, 1985). The Ridge and Valley has similar rock types to the Appalachian Plateau, but does not have coal as a defining rock type and instead has limestone (Smith & Ellison, 1985). Limestone rocks are known for producing karst topography that allows surface water to infiltrate the aquifers spreading any pollutant over wide areas (Virginia Department of Mines, Minerals, and Energy, 2015). In addition, source rock aquifers of shale, slate, limestone and dolomite are strontium bearing. Limestone is part of a group of rocks called carbonates, which are defined as strontium bearing rock types (Wiegand, 2009). The Blue Ridge and Piedmont both have igneous and metamorphic rocks of Precambrian ages (Smith & Ellison, 1985). Igneous and metamorphic rocks are not common sources of strontium. Finally, the Coastal Plain is comprised of unconsolidated sediments, commonly sands (Smith & Ellison, 1985). Watts & Howe (2010) state that sandstones can be sources of strontium in drinking water, and unconsolidated sands are the precursor to sandstones. The rock types in the western and coastal parts of Virginia are potential sources of strontium and create physical vulnerability in the state (Smith & Ellison, 1985).

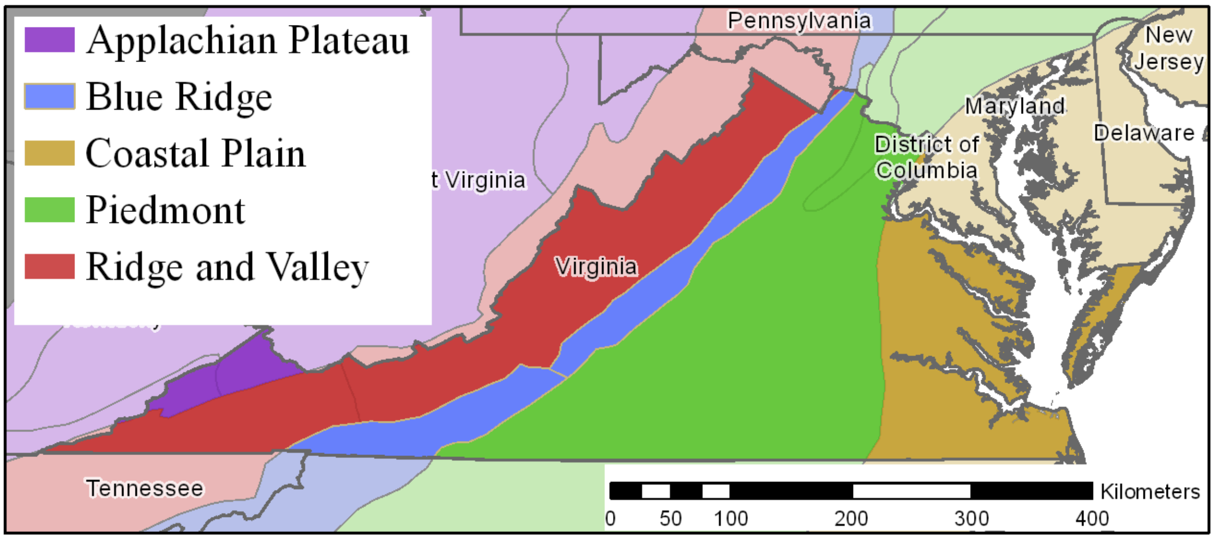

Figure 1: Map of Physiographic Provinces in Virginia

2.3.2 Social Vulnerability

Populations that are most vulnerable to strontium contamination are those that have high numbers of children (who absorb strontium at higher rates) as well as those with high rates of poverty and limited access to nutritious food (since diets low in protein and calcium allow strontium to replace calcium in bone growth) (Health & Services, 2000; Watts & Howe, 2010). Roughly, 21% of Virginia's population is under the age of 18, which amounts to nearly 1.8 million residents. This figure includes the nearly 6% of Virginia's population that is under age five, which amounts to more than 500,000 residents (United States Census Bureau (USCB), 2018). In Virginia, 850,000 people live in poverty (total family income less than family income threshold defined by family size and federal poverty line), which is more than 10% of the total population (USCB, 2018). There are also four counties classified as 'economically depressed' in 2019 by the Appalachian Regional Commission and an additional six counties at risk of becoming economically depressed (Appalachian Regional Commission, 2018). According to the USDA, approximately 17.8% of Virginians live in a food desert, which is defined as an area with low access to food and low income (Ver Ploeg & Rhone, 2017). Food deserts are located in every region of the state (Ver Ploeg & Rhone, 2017).

More than 30% of children in Virginia live in poverty with 36% of children under six living in poverty (National Center for Children in Poverty, 2018). Virginia has several counties, predominantly in two areas of the state, with high rates of children living in poverty (i.e., over 20% of children in poverty) (Voss, Long, Hammer, & Friedman, 2006). The Appalachian region which includes counties such as Lee, Scott, and Wise, and the southeast region which includes the counties of Greenville, Southampton, and Sussex, among others(Voss et al., 2006). High childhood poverty rates have been linked to malnutrition, driven by diets low in calcium and protein (Peña & Bacallao, 2002). Diets low in calcium and protein make individuals more susceptible to the health effects of strontium and increase the prevalence of rickets due to strontium exposure (Health & Services, 2000; Watts & Howe, 2010).

Low income and poor diet are not the only social vulnerabilities to strontium in Virginia. Nearly 1.7 million Virginians get their drinking water from private water systems that are not regulated under the SDWA (Benham et al., 2016; Pieper, Krometis, Benham, et al., 2016). The water quality produced by private water systems is not regulated by the federal government or Virginia state government, which means that each person who relies on a private water system is responsible for all water quality testing, treatment, and maintenance (Benham et al., 2016). Up to 80% of Virginians who rely on private water systems for drinking water have never had their water tested or tested it only once, meaning that they are unaware of the risks they may potentially face from their drinking water (Benham et al., 2016). These residents are thus unaware of the level of strontium in their water and the dangers associated with ingesting high levels of strontium, which means that they are not making changes to protect themselves or their children. Together, the high number of people in Virginia with private water supply systems coupled with high rates of childhood poverty creates high vulnerability to health effects caused by elevated levels of strontium.

2.4 Research Questions

While public drinking water is routinely monitored and treated to achieve SDWA standards, private drinking water supply systems are not required to be formally monitored. The owners of private systems are responsible for covering all costs of water testing and treatment and they also must take on the added responsibility of understanding the reasons to test and treat water, learn how to interpret test results, and decide when and what actions may need to be taken to ensure safe drinking water. In Virginia, most residents with private drinking water systems have never or only once tested the quality of their water, so they are largely unaware of the health risks they may face. Strontium, which occurs naturally in the environment, can cause health problems when consumed in concentrations greater than 1.5 mg/L in water. The lack of understanding of the risks of strontium contamination in private drinking water sources in Virginia led to the following research questions:

1. What is the level of strontium in private drinking water systems in Virginia?
2. What are the physical vulnerabilities to strontium contamination in private drinking water systems in Virginia?
3. What are the social vulnerabilities to strontium contamination in private drinking water systems in Virginia?

3. Assessing Strontium and Vulnerability to Strontium in Private Drinking Water Supplies in Virginia

3.1 Introduction

Water is integrated into every aspect of our lives and clean drinking water is essential to a healthy life. Hundreds of thousands of people die from contaminated drinking water every year; the United Nations (UN) estimates that 502,000 people die due to diarrhea from contaminated drinking water each year (UN, 2018). In the United States the Environmental Protection Agency (EPA) enforces the Safe Drinking Water Act (SDWA) that regulates public drinking water supply systems (United Sates SDWA, 1974). As knowledge about contaminants increases and treatment techniques improve, the EPA adds new contaminants to the SDWA every five years (United States EPA, 2014). Contaminants that are shown to be detrimental to human health, can be found in waters throughout the United States, and pose a meaningful opportunity to improve public health, are added to the SDWA (United States EPA, 2014). The third round of new contaminant candidates included strontium because of the detrimental impact it has on bone growth (Health & Services, 2000; United States EPA, 2014). However, The SDWA only applies to public drinking water systems, and 1.7 million Virginia residents use private water supply systems like wells, cisterns, and springs for their drinking water (Benham et al., 2016). More effectively, characterizing private water supply water quality has the potential to benefit public health.

While there are a limited number of state and regional scale studies examining private water supply system quality (Allevi et al., 2013; Benham, Ling, Ziegler, & Krometis, 2016; Clark et al., 2009; Desimone, Mcmahon, & Rosen, 2015; Johnson & Belitz, 2015, 2017; Pieper, Krometis, & Edwards, 2016; Pieper, Krometis, Gallagher, Benham, & Edwards, 2015; Pieper, Krometis, Benham, & Gallagher, 2016; Smith et al., 2014; VanDerwerker, Zhang, Ling, Benham, & Schreiber, 2018), no nation-wide assessment exists. There have been even fewer studies that examine strontium at large scales (Fontenot et al., 2013; Hildenbrand et al., 2016; Knobeloch et al., 2013) and none that investigate strontium in PDW in Virginia. Virginia Cooperative Extension's Virginia Household Water Quality Program provides an opportunity to understand the distribution of strontium concentrations in PDW in Virginia. This study addresses the following questions:

1. What is the level of strontium in private drinking water systems in Virginia?
2. What are the physical vulnerabilities to strontium contamination in private drinking water systems in Virginia?
3. What are the social vulnerabilities to strontium contamination in private drinking water systems in Virginia?

3.2 Literature Review

Strontium is a naturally occurring alkaline earth metal element closely related to calcium (Health & Services, 2000). The natural abundance of strontium in the Earth's crust is 0.02-0.03%, and the average concentration of strontium in fresh water globally is 0.5 - 1.5 mg/L (Health & Services, 2000; Watts & Howe, 2010). Strontium is present in many sedimentary rocks and in especially high levels in some calcite minerals (Health & Services, 2000; Watts & Howe, 2010; Wiegand, 2009). Anthropogenic sources of strontium include nuclear fallout, fertilizers, and industrial manufacturing (Hosono et al., 2007; Jiang, 2011; Volokh et al., 1990; Watts & Howe, 2010).

Health problems associated with strontium have been identified as a risk to public health (United States EPA, 2014). Under standard environmental levels, strontium is not toxic to humans (Health & Services, 2000). However, when concentrations exceed 1.5 mg/L in water, strontium can enter the bloodstream and replace calcium in bones, making bones brittle eventually leading to the development of strontium rickets (Health & Services, 2000; Watts & Howe, 2010). Strontium is particularly dangerous to children, especially infants, since their bodies have higher rates of absorption into the bloodstream and they experience higher rates of bone growth than adults (Health & Services, 2000; Watts & Howe, 2010). Due to the potential public health impact of strontium in drinking water, the EPA added strontium to the Third Drinking Water CCL, but has not decided yet if it will regulate strontium (United States EPA, 2014). Strontium can be removed from drinking water through water treatments such as lime softening (O'Donnell et al., 2016). The negative impacts of high concentrations of strontium in water can be mitigated by reducing the amount of strontium the body absorbs by consuming a diet high in protein and calcium (Health & Services, 2000; Watts & Howe, 2010).

Virginians are at risk of elevated strontium levels in drinking water due to Virginia's physical environment. There are five physiographic provinces in Virginia: the Appalachian Plateau, Ridge and Valley, Blue Ridge, Piedmont, and Coastal Plain (Fenneman & Johnson, 1946; Smith & Ellison, 1985). The Appalachian Plateau and Ridge and Valley provinces are characterized by shale, slate, coal, and limestone, which constitute rock types known to be sources of strontium (Smith & Ellison, 1985; Watts & Howe, 2010). The Coastal Plain is characterized by sandstones and unconsolidated sands, which can contain high levels of strontium (Smith & Ellison, 1985; Watts & Howe, 2010). The Blue Ridge and Piedmont are characterized by igneous and metamorphic rocks that contain strontium that is not readily mobilized in water due to the mineralogy (Smith & Ellison, 1985). Furthermore, there are more than 8 million acres of agricultural land use in Virginia that potentially receive phosphate fertilizers, that can potentially contain high levels of strontium, that can lead to high concentrations of strontium in nearby water sources (Hosono et al., 2007; Jiang, 2011; Pease, 2009; Volokh et al., 1990). Studies have shown that the type of phosphate fertilizer (e.g. monoammonium phosphate, diammonium phosphate, and triple superphosphate), the amount applied, and the cumulative legacy of fertilizer use, can contribute up to one quarter of the strontium found in drinking water (Böhlke & Horan, 2000; Hosono et al., 2007).

With 6% of the population of Virginia under the age of five and more than 10% of the population living below the poverty line, there are many individuals vulnerable to the health effects of strontium (USCB, 2018). Nearly 18% of Virginians who live in urban areas live more than one mile from a grocery store and in rural areas the distance to a grocery store can exceed 10 miles. As a result some Virginians may lack access to diets high in calcium and protein that can prevent the damage strontium causes to bones (Health & Services, 2000; Ver Ploeg & Rhone, 2017; Watts & Howe, 2010). Additionally, Figure 2 shows that there are several counties that have childhood poverty rates above 20% both in the Appalachian region and southeastern regions of Virginia (Voss et al., 2006). Another social vulnerability is the number of people in Virginia that rely on private water systems for their drinking water. Private systems, which are not monitored or regulated by the federal or Virginia state governments, service nearly 1.7 million Virginians (Benham et al., 2016; Pieper, Krometis, Benham, et al., 2016).

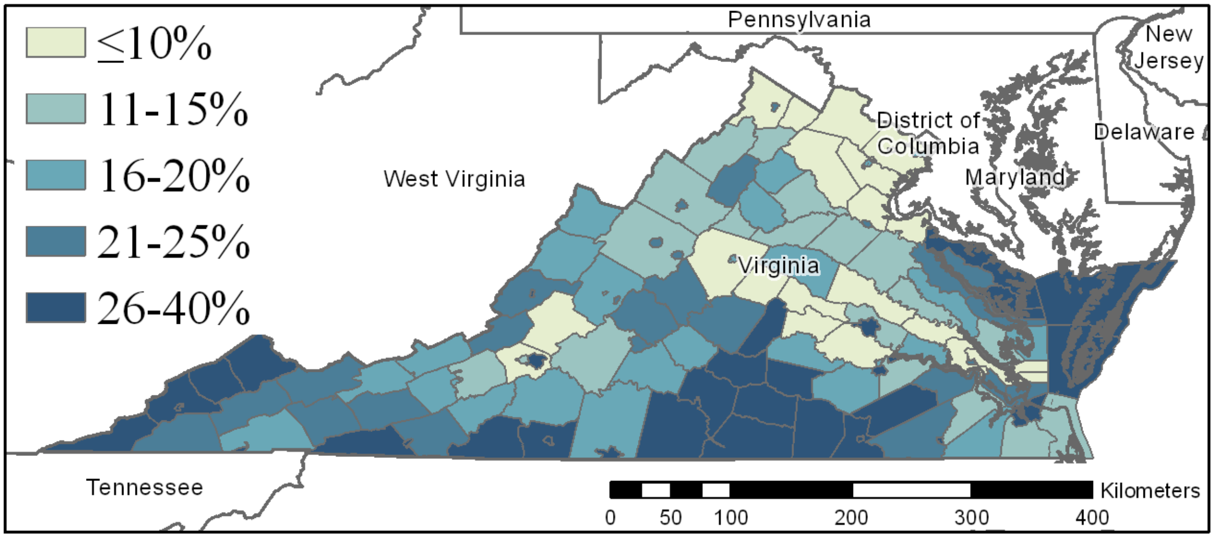

Figure 2: Map of childhood poverty rates in Virginia

Virginia exhibits the physical characteristics that are associated with elevated levels of strontium in water sources and has significant socially vulnerable populations. This research investigates the level of strontium in private drinking water systems in Virginia, by characterizing the prevalence of strontium in private drinking water systems in Virginia and examining the physical and social vulnerabilities to strontium contamination present in private drinking water systems.

3.3 Methods and Analysis

3.3.1 Data Collection

Water samples used in this analysis were collected through the Virginia Household Water Quality Program (VAHWQP) between 2014-2018. VAHWQP was established as a Virginia Cooperative Extension effort in 1989 and is operated by the Department of Biological Systems Engineering at Virginia Tech (Benham et al., 2016). The program conducts roughly 65 drinking water clinics per year samples have been submitted from every Virginia county (Benham et al., 2016). The VAHWQP drinking water clinics provide private well owners with low cost water quality tests as well as objective maintenance, care, and quality information for their private water supply systems (Benham et al., 2016). Participants fill the four bottles provided in the test kit with water from the tap where they typically obtain their drinking water. One 250 mL sample is collected immediately after the tap has been turned on after at least six hours of stagnation (no water use; first draw). A second 250 mL sample collected after the water has run through the pipes for one minute (flush). The first draw and flush samples are collected in order to help understand how the water is interacting with the pipes in the household and whether metals present are likely coming from household plumbing materials or the groundwater itself. Two additional samples are also collected after the flush sample for analysis of remaining contaminants. Samples are then transported on ice to Virginia Tech for analyses. The 250 mL samples are acidified and subsampled for metal and elemental analysis. A 125 mL sample is used to analyze pH, electroconductivity, and anions (Fl and NO_3N). The final bottle is used to test for the presence of bacteria. The geolocation, well information, and laboratory results are stored in an Access database that is stored on a password protected server. Sample addresses were converted to GPS latitude-longitude coordinates using geocod.io web based software and displayed at the state level preventing individual households from being identified and ensuring confidentiality of participants. In order to protect the identity of participants, all personal, identifying information including addresses was removed from the dataset before any analyses were conducted.

Supplemental data sources were collected from the United States Geological Survey (USGS), United States Census (USCB), and United States Department of Agriculture (USDA). A geologic map shapefile containing rock types and rock ages was downloaded from the USGS website (Dicken et al., 2005). The USGS National Land Cover Database (NLCD) 2011 raster file that identifies land cover from 2006 to 2011 in 30-meter cell resolution using Landsat imagery from 2011 was obtained (USGS, 2011). The last USGS dataset was the physiographic province shapefile digitized from Fenneman's map "Physical Divisions of the United States" that divided the country into areas of distinct topography, rock types and structures, and geologic history (USGS, 2004). TIGER line data for census tracts--which provides social, economic, and demographic attributes--was gathered as a shapefile from the US Census (USCB, 2010). Finally, data on food deserts were collected as a CSV file from the USDA, and the land use land cover data were downloaded as a raster dataset from the USDA as well (USDA, 2017).

3.3.2 Data Processing

Data received from VAHWQP came in two CSV files, one set of samples collected between January 2014 and August 2017 and the other set collected September 2017 and December 2018. These files were merged to create a master CSV file for the study containing 9,804 samples. Thirteen had no first draw strontium data collected and 12 samples had no flush strontium data collected, so those samples were removed leaving a final 9,779 samples. All cells left blank or containing "n/a" were replaced with a value of -1 for ease of analysis. To increase the speed of analyses, many fields of information that were not relevant to this project were removed. For example, data on well characteristics (e.g. age, depth), household demographics, water taste, odor, and color, among other things, were removed from the dataset and all statistical and spatial analyses.

The 9,779 samples were input into AcrMap 10.5.1 using the "import x-y data" tool. The TIGER line census tract shapefile and food desert supplemental CSV file were added to ArcMap 10.5.1 and joined using the 11-digit county code number. The original extent of the physiographic provinces shapefile was the entire continental US, so the Clip tool was used to select only provinces that lie within the boundaries of the state of Virginia using the census tract shapefile as the clip extent. The extent of the geology shapefile also included several neighboring states so the Clip tool in ArcMap 10.5.1 was used to remove data unnecessary for this analysis.

3.3.3 Statistical Analysis

Strontium data summaries were produced using RStudio 1.0.153. These data included the minimum and maximum values, mean, median, and first and third quartile values. Jarque Bera and Quantile-Quantile plots were used to describe the distribution of the data.

Concentrations of strontium were plotted against other compounds to identify relationship patterns both in first draw and flush samples. The R Squared value was determined for each plot using RStudio 1.0.153. A regression line was fit to each set of data and the R Squared value was the calculation of how closely the data statistically fit that regression line. The statistical summary and exploratory data analyses gave both a statistical and a visual representation of strontium in the private drinking water samples.

RStudio 1.0.153 was used to conduct Kruskal-Wallis analyses. The Kruskal-Wallis test is statistical test to compare two populations and unlike t-tests, does not require the two populations to have normal distributions. A confidence interval of 95% was used for the Kruskal-Wallis analyses. In addition, RStudio was used to conduct a t-test analysis on the samples with water softeners and without water softeners. This test was used to determine if the water softeners are removing strontium from drinking water.

3.3.4 Spatial Analysis

Anselin Local Moran's I and Global Moran's I tests were conducted using ArcMap 10.5.1. Anselin Local Moran's I is a tool to identify the locations of outliers, hot spots, and cold spots given feature locations and attributes. Global Moran's I is a measure of spatial autocorrelation based on feature locations and attributes. This tool can determine if the data are distributed randomly, dispersed, or clustered.

The land cover analysis was conducted in ArcMap 10.5.1 and Excel 2016. The LAND_COVER field data was extracted for the state of Virginia and put into Excel for analysis. Then the Ridge and Valley land cover was extracted through the ArcMap Extract by Mask tool and follows the same pattern as before with the LAND_COVER field data extracted and stored in Excel. The land cover data for the VAHWQP samples (all samples and high strontium samples) was collected using the Extract to Point ArcMap tool, then using the Summarize tool on the LAND_COVER field with the FID first value. The four land cover data sets, Virginia, the Ridge and Valley, all VAHWQP samples, high strontium and VAHWQP samples, are combined in Excel and the percentage of each land cover type in the Ridge and Valley and the high strontium samples using a simple calculation in the field. To determine the geologic influence to strontium contamination, a similar method is used, with the exception that the values are extracted using the Select by Location tool and Summarizing the selected data on both the UNIT_AGE and ROCKTYPE1 fields by the sum of the AREA field.

The food desert CSV from the USDA contained several measures of poverty, three of which were used in this analysis: percentage of population in poverty, percentage of households without access to a vehicle (HUNV), and percentage of households receiving Supplemental Nutrition Assistance Program (SNAP) benefits. The SNAP is a federal program through the USDA that combats food insecurity for low income individuals (USDA, 2018). The number of households without access to a vehicle was included to find households that do not have enough income to afford a vehicle, but earn too much to fall below the poverty line. Individuals living in these households could potentially have a difficult time accessing diets high in calcium and protein, necessary to limit the absorption of strontium, and would be less likely to be able to afford water treatment needed to lower excessively high strontium concentrations in present in their PDW.

The percentage of people under the age of 18 in each census tract was calculated using the calculate field tool in ArcMap as a rate of the TractKids field and POP2010 field. The rate of HUNV and the rate of households receiving SNAP benefits were also calculated using the calculate field tool in ArcMap but this time using the TractHUNV (for households without access to a vehicle), TractSNAP (for households collecting SNAP benefits), and OHU2010 (for the number of households in each tract) fields.

The percentage of the population under 18, poverty rate, HUNV rate, and SNAP rate were displayed using 5 color categories with approximately the same number of counties in each color bracket while still maintaining whole numbers as percentage breaks. The Anselin Local Moran's I tool was run on all four categories outlined to find hotspots, cold spots, and outliers. The select by attribute tool was used to select high outliers and high clusters for each of the categories for the state of Virginia. The total number of census tracts and the number of selected census tracts for each category was entered into an Excel sheet. Then, the select by location tool was used to identify census tracts in the Ridge and Valley, tracts that participated in the VAHWQP, and that had a high strontium value in that census tract. For each of these three selections the select by attribute tool was used to determine the number of high outliers and high clusters in that subset of census tracts. Finally, the total number of census tracts and the number of selected census tracts for each category and each subset of census tracts was entered into an Excel sheet where percentages of census tracts were calculated.

3.4 Results

3.4.1 Strontium Concentration

Of the 9,779 PDW samples, 122 first draw and 124 flush samples exceeded the proposed EPA RHL of 1.5 mg/L. The highest concentration in a flush sample was a value of 29.71 mg/L, and the highest concentration in a first draw 28.75 mg/L. However, the vast majority (99%) of samples had strontium concentrations below the proposed RHL. The Jarque Bera and Quantile-Quantile analyses determined that concentrations of strontium in both first draw and flush samples had non-normal distributions with a left skew. The left skew of the data and boxplot indicate that there are outliers. These outliers produce a mean that is nearly four times larger than the median since the mean is more sensitive to outliers. The correlation of strontium concentrations in first draw and flush samples has an R squared of 0.984 that indicates a high degree of correlation between the two. The Kruskal-Wallis test produced a p-value of <0.001, indicating that the samples are statistically similar. After determining that the two sets of strontium samples are similar, the remaining analyses focused on first draw samples.

There were 2,350 samples that had water softeners and they were distributed throughout the state with higher concentrations along the coast and in the Ridge and Valley province. Of the 2,350 samples, 45% of them fell in the Ridge and Valley. Approximately 30% of samples that were above the 1.5 mg/L proposed RHL also had water softeners. The samples had significantly different means with a p-value of <0.001. The samples with water softeners had an average concentration of 0.096 mg/L while the samples without a water softener had an average concentration of 0.180, or double the concentration of the samples with water softeners.

Table 1: Statistical summary of strontium first draw and flush samples

	Strontium first draw	Strontium flush
Range	0.000 - 28.750	0.000 - 29.710
1st Quartile	0.014	0.014
Mean	0.158	0.160
Median	0.043	0.044
3rd Quartile	0.109	0.109
Standard Deviation	0.808	0.833
Number of High Strontium Samples	122	124
Total Number of Samples	9779	9779

The locations of the 120 first draw strontium samples with concentrations greater than 1.5 mg/L were plotted Figure 3. High concentrations of strontium are found from the southwest to the northwest part of the state. A Global Moran's I test on first draw samples produced a p-value of <0.001 and z-score of 24.574, which indicates that there is <1% chance that clustered patterns are the result of random chance. A Local Moran's I test mapped the High-High clusters (Figure 4), or areas where samples with high concentrations of strontium are near other high concentration samples, in a southwest to northwest trend similar to the strontium samples greater than 1.5mg/L shown in Figure 3. The Ridge and Valley province follows the western border of the state that contains 70% of the high clusters and 80% of the low outliers.

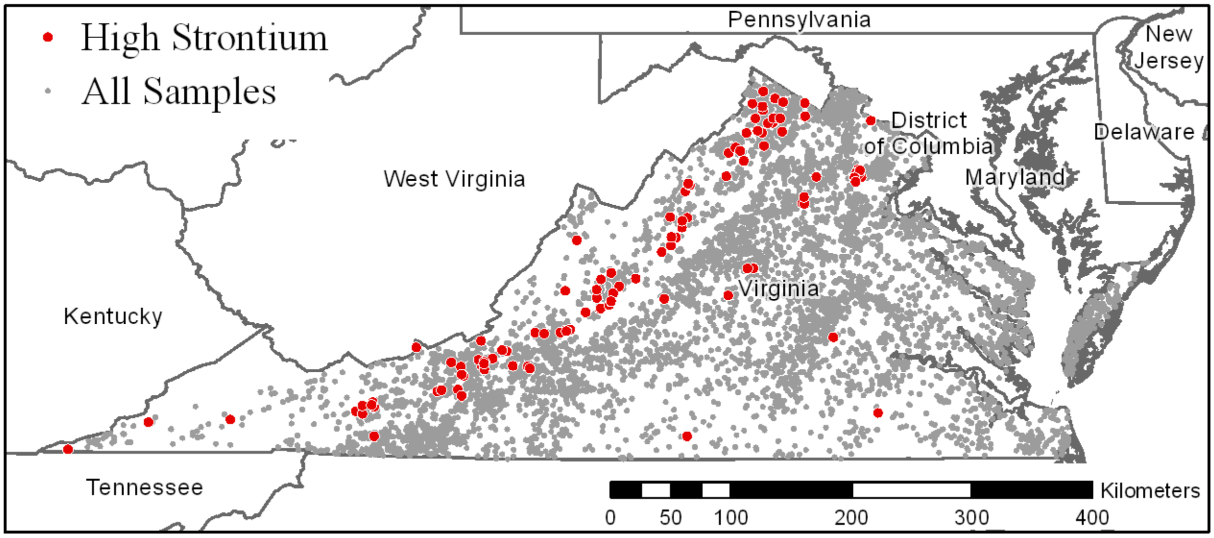

Figure 3: Map of 9,779 water quality samples collected from the VAHWQP between 2014 and 2018

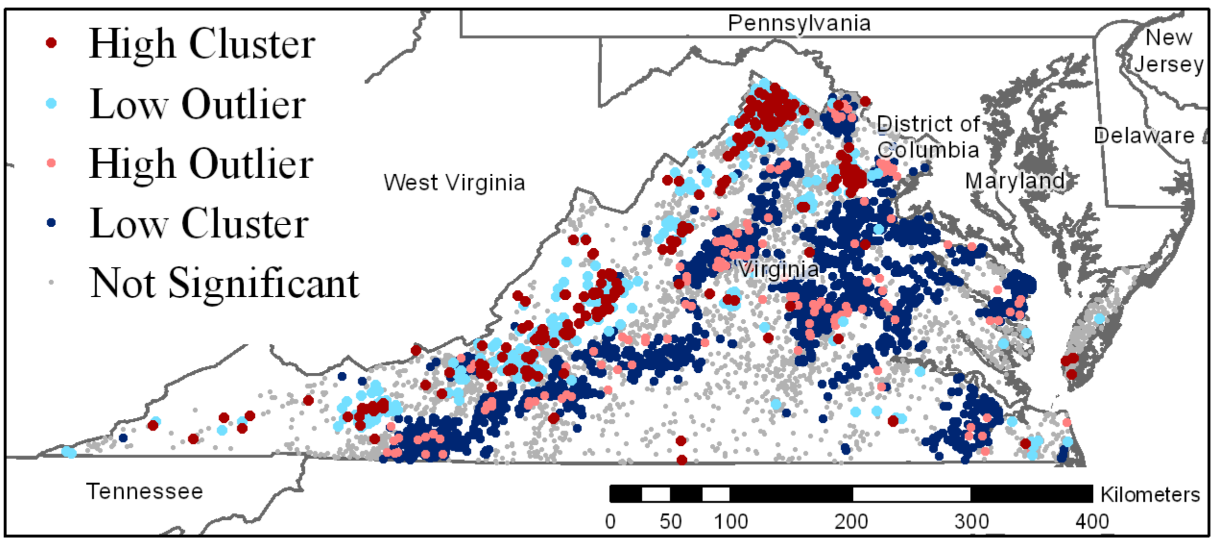

Figure 4: Results of cluster analysis of strontium concentrations in first draw samples

3.4.2 Physical Vulnerability

Strontium is weakly correlated (R squared of >0.100 and p-value <0.500) with calcium and magnesium while having no correlation (R squared <0.100 and p-value >0.500) with 29 other water quality parameters that were tested (Table 2). Jarque Bera tests and Quantile-Quantile plots were used to determine the normality of sample concentrations for the 29 water quality parameters. With all compounds having non-normal distributions, Kruskal-Wallis tests were run to determine the statistical correlation between strontium and each analyzed water quality parameters. Based on Kruskal-Wallis tests, 13 parameters were not statistically similar to strontium. However, after comparing these results to R squared analyses, the relationship between the parameters and strontium is not clear.

Land use analysis (Table 3) found that deciduous forest, hay/pasture, and developed open space are the predominant land cover types having strontium concentrations at least twice the rate of the next most common land cover type. High strontium samples most commonly occur on hay/pasture, herbaceous, low intensity development, and medium intensity development land cover types. Only 1% of samples from deciduous forest and developed open space have high strontium concentrations, which is about half the rate of occurrence for hay/pasture, herbaceous, low intensity development, and medium intensity development land cover types. The most prevalent land cover types in the Ridge and Valley Province mirror the land cover types for all VAHWQP samples. Deciduous forest and hay/pasture land cover types occur at higher rates in the Ridge and Valley province compared to the rest of the state.

Table 2: Statistical analysis results for components of water quality and their relationship to strontium

Component	First Draw				Flush			
	R^2	r	Jarque Bera p-value	Kruskal Wallis p-value	R^2	r	Jarque Bera p-value	Kruskal Wallis p-value
Fl	0.003	0.098*	< 0.000	0.000**	NA	NA	NA	NA
Na	0.000	-0.207	< 0.000	0.000**	0.000	-0.206	< 0.000	0.000**
Mg	0.092	0.717*	< 0.000	0.000**	0.094	0.722*	< 0.000	0.000**
Al	0.000	-0.020	< 0.000	0.998	0.000	-0.034	< 0.000	0.999
Si	0.002	0.120	< 0.000	0.179	0.002	0.127	< 0.000	0.327
P	0.001	0.029	< 0.000	0.676	0.001	0.003	< 0.000	0.480
SO4	0.087	0.095	< 0.000	0.003**	0.079	0.089	< 0.000	0.012**
K	0.000	0.457	< 0.000	0.000**	0.000	0.456	< 0.000	0.000**
Ca	0.122*	0.813*	< 0.000	0.000**	0.113*	0.803*	< 0.000	0.000**
V	0.000	0.068	< 0.000	0.561	0.000	0.074	< 0.000	0.825
Cr	0.000	0.004	< 0.000	1.000	0.000	0.001	< 0.000	1.000
Fe	0.000	0.160	< 0.000	0.194	0.000	0.165	< 0.000	0.142
Mn	0.000	0.350	< 0.000	0.468	0.001	0.385	< 0.000	0.077**
Co	0.000	0.210	< 0.000	0.004**	0.000	0.286	< 0.000	0.000**
Ni	0.000	-0.086	< 0.000	0.919	0.000	0.383	< 0.000	0.000**
Cu	0.000	0.005	< 0.000	0.677	0.000	-0.048	< 0.000	0.790
Zn	0.000	0.090	< 0.000	0.774	0.000	0.137	< 0.000	0.956
As	0.000	0.083	< 0.000	0.000**	0.000	0.107	< 0.000	0.000**
Mo	0.000	-0.019	< 0.000	0.028**	0.000	0.081	< 0.000	0.076**
Ag	0.000	0.053	< 0.000	1.000	0.000	0.024	< 0.000	0.999
Cd	0.000	0.041	< 0.000	1.000	0.000	0.078	< 0.000	1.000
Sn	0.000	-0.032	< 0.000	1.000	0.000	0.061	< 0.000	0.905
Pb	0.000	0.796*	< 0.000	0.963	0.008	0.018	< 0.000	1.000
Hardness	0.125*	0.116	< 0.000	0.250	0.119*	0.797*	< 0.000	0.094**
Cl	0.009	0.164	< 0.000	0.043**	0.010	0.110	< 0.000	0.045**
Ti	0.004	0.971*	< 0.000	0.982	0.002	0.181	< 0.000	0.853
Se	0.000	0.023	< 0.000	0.677	0.000	0.021	< 0.000	0.240
Sr	0.984*	0.971*	< 0.000	0.000**	NA	NA	< 0.000	NA
Ba	0.012	0.547	< 0.000	0.000**	0.013	0.557	< 0.000	0.000**
U	0.000	0.175	< 0.000	0.000**	0.000	0.173	< 0.000	0.000**

* Significant correlation $R^2 > 0.100$ or $r > 0.700$

** Significant p-value < 0.05

Table 3: Results of land use analysis

	All Pixels in Virginia	All Ridge and Valley Pixels	% Occurring in Ridge and Valley	All VAHWQP Samples	All High Strontium VAHWQP	% Occurring on High Samples
Cultivated Crops	4912780	302283	6.152	658	6	0.912
Evergreen Forest	11723582	1386292	11.825	455	5	1.099
Developed, Medium Intensity	984856	210559	21.380	48	1	2.083
Herbaceous	2239702	500955	22.367	97	2	2.062
Developed, Open Space	6806563	1563401	22.969	1684	20	1.188
Developed, Low Intensity	2776031	719308	25.911	543	10	1.842
Deciduous Forest	51494647	18284969	35.508	2764	30	1.085
Hay/Pasture	19752866	7357204	37.246	2624	45	1.715
Total	117084977	31507802	26.910	9630	120	1.246

Table 4 show that shale underlies the most land area in Virginia, but there are also formations of sand, sandstone, and gravel throughout the state. Sand, gravel, and shale are the most common rock types for the VAHWQP samples, each having more than 100 samples. The most common rock types for high strontium samples are limestone, dolomite, sandstone, shale, and black shale, in order of frequency normalized to total occurrences (Figure 5). Alluvium, anorthosite, conglomerate, quartz monzonite, metasedimentary, and mylonite rocks only had a single occurrence of a high strontium value and were thus excluded from analysis. The most common rock types in the Ridge and Valley province are shale, sandstone, dolomite and limestone, with shale comprising most area of the region.

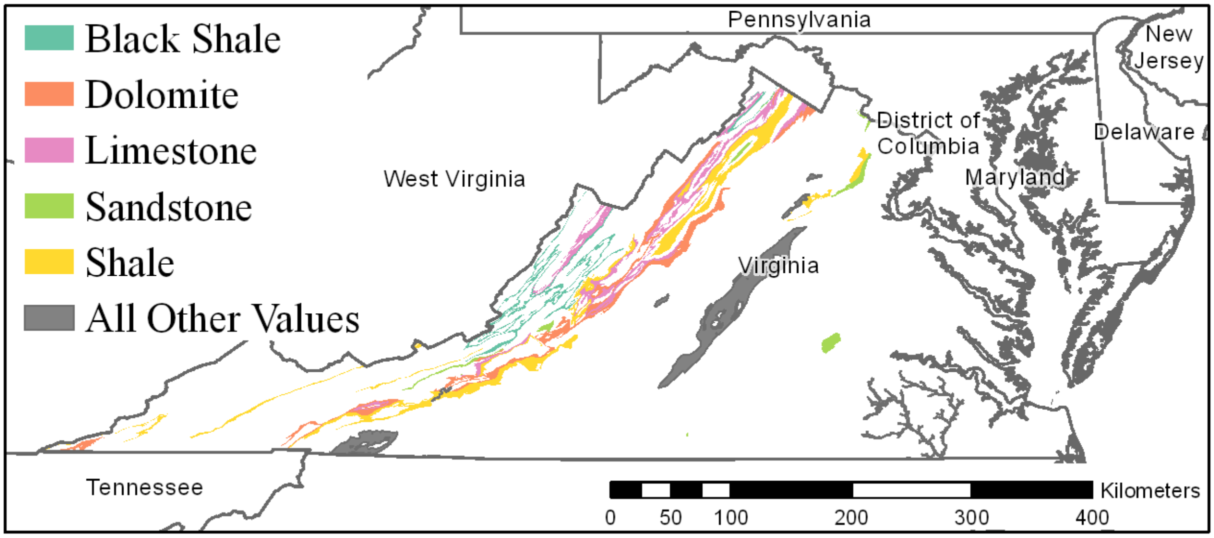

Figure 5: Map of the rock formations that contain at least one high concentration strontium sample (first draw concentration > 1.5 mg/L)

Table 5 illustrate that the age of rocks in Virginia vary widely, with Quaternary being the most common unit age but Cambrian covering a larger area. There are six age categories that have similar occurrences for all VAHWQP samples (Ordovician, Proterozoic Z, Tertiary, Proterozoic Y, Quaternary, and Cambrian) spanning more than 2.5 billion years of time. Geologic formations associated with the Cambrian and Ordovician time periods have the most high strontium samples, with 35 of the 102 high concentration samples falling on rocks originating during those periods. The most common age for rocks in the Ridge and Valley is Ordovician closely followed by Cambrian in both count and area. This mirrors the distribution of high concentration strontium samples, indicating a strong correlation.

Table 4: Results of rock type analysis

Rock Type	All Virginia Occurrences	Area of Rock Formation in Virginia	Ridge and Valley Occurrences	Area of Rock Formation in Ridge and Valley	Percent of Formation Area in Ridge and Valley	All VAHWQP Occurrences	Area of Rock Formation on VAHWQP	High Strontium VAHWQP Occurrences	Area of Rock Formation on High Strontium Samples	Percent of Formation Area on High Strontium Samples
Alluvium	118	0.115	0	0.000	0.000	12	0.051	1	0.043	83.900
Anorthosite	2	0.004	0	0.000	0.000	1	0.003	1	0.003	100.000
Black Shale	98	0.186	97	0.185	99.863	17	0.145	2	0.094	65.052
Conglomerate	87	0.051	0	0.000	0.000	21	0.032	1	0.006	17.679
Dolostone (Dolomite)	234	0.655	223	0.650	99.332	82	0.599	15	0.196	32.668
Limestone	223	0.455	216	0.454	99.859	50	0.346	13	0.181	52.235
Meta-Argillite	97	0.499	0	0.000	0.000	39	0.478	1	0.175	36.498
Metasedimentary Rock	40	0.047	0	0.000	0.000	15	0.037	1	0.002	6.595
Mylonite	40	0.152	1	0.000	0.320	14	0.138	1	0.002	1.179
Quartz Monzonite	5	0.048	0	0.000	0.000	1	0.047	1	0.047	100.000
Sandstone	557	0.694	268	0.455	65.546	72	0.346	9	0.049	14.031
Shale	468	1.341	394	1.268	94.505	101	1.039	12	0.296	28.524
Water	305	1.341	14	0.004	0.269	25	1.304	1	0.001	0.106
Total	5703	11.783	1353	3.433	29.136	1252	9.507	59	1.094	11.511

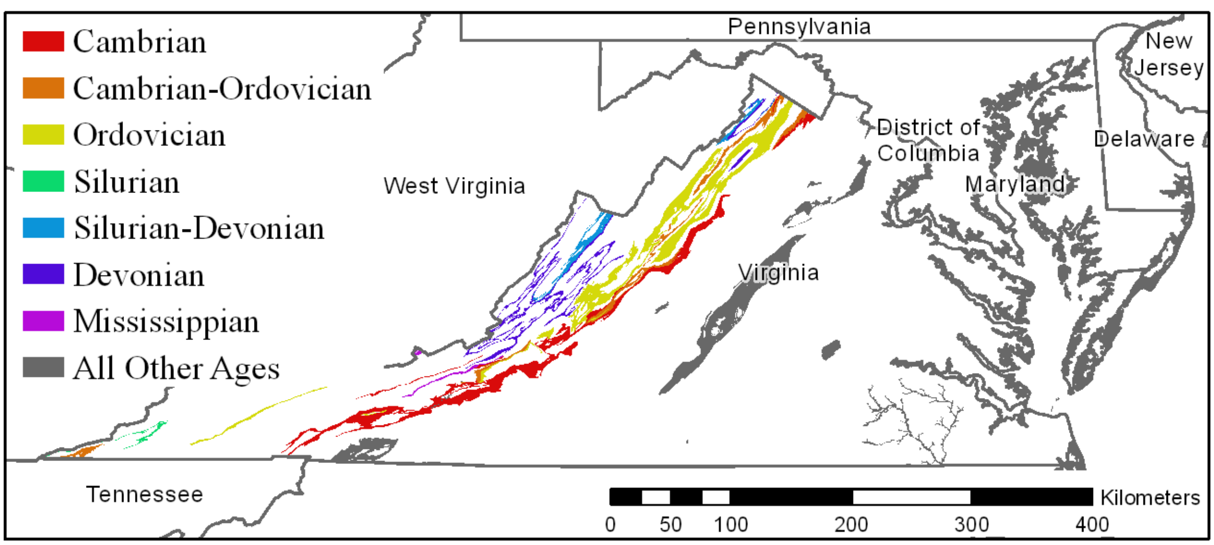

Figure 6: Map of the rock formations that contain at least one high concentration Sr sample (first draw concentration > 1.5 mg/L)

Table 5: Results of rock age analysis

Rock Formation Age	All Virginia Occurrences	Area of Rock Formation in Virginia	Ridge and Valley Occurrences	Area of Rock Formation in Ridge and Valley	Percent of Formation Area in Ridge and Valley	All VAHWQP Occurrences	Area of Rock Formation on VAHWQP	High Strontium VAHWQP Occurrences	Area of Rock Formation on High Strontium Samples	Percent of Formation Area on High Strontium Samples
Proterozoic Z-Cambrian	504	0.960	9	0.079	8.182	99	0.858	1	0.175	20.348
Proterozoic Y	474	0.921	32	0.096	10.375	149	0.814	2	0.051	6.219
Proterozoic - Paleozoic ?	40	0.152	1	0.000	0.320	14	0.138	1	0.002	1.179
Cambrian	591	1.396	246	0.688	49.262	162	1.148	14	0.244	21.265
Cambrian-Ordovician	148	0.375	108	0.317	84.420	46	0.338	8	0.088	26.136
Ordovician	442	0.797	374	0.726	91.050	100	0.633	13	0.269	42.536
Ordovician-Devonian	10	0.002	10	0.002	100.000	2	0.000	1	0.000	27.370
Silurian	85	0.178	76	0.175	98.369	3	0.011	1	0.010	92.945
Silurian-Devonian	116	0.196	116	0.196	100.000	10	0.115	3	0.041	35.872
Devonian	168	0.631	168	0.631	100.000	46	0.472	3	0.099	20.932
Mississippian	110	0.245	97	0.158	64.552	12	0.146	2	0.012	7.944
Upper Triassic	175	0.210	0	0.000	0.000	46	0.051	5	0.035	68.501
Triassic	53	0.069	0	0.000	0.000	14	0.155	2	0.022	14.401
Holocene	305	1.341	14	0.004	0.269	25	1.304	1	0.001	0.106
Quaternary	907	0.966	0	0.000	0.000	155	0.589	1	0.043	7.241
Total	5754	11.833	1353	3.433	29.012	1252	9.507	59	1.094	0.001

3.4.3 Social Vulnerability

Fifteen percent of the 1,971 Virginia census tracts spread throughout the state shown in Figure 7 are considered food deserts, which are geographic areas with low access to food. Here, food deserts are defined as census tracts with 500 residents (33% of the tract population) that live at least one mile in an urban area and 10 miles in a rural area from a grocery store. Furthermore, in food deserts, 20% or more of the population must fall below the federal poverty line or have a median family income less than 80% of the statewide median family income. More than 20% of census tracts with high strontium samples are food deserts (Table 6).

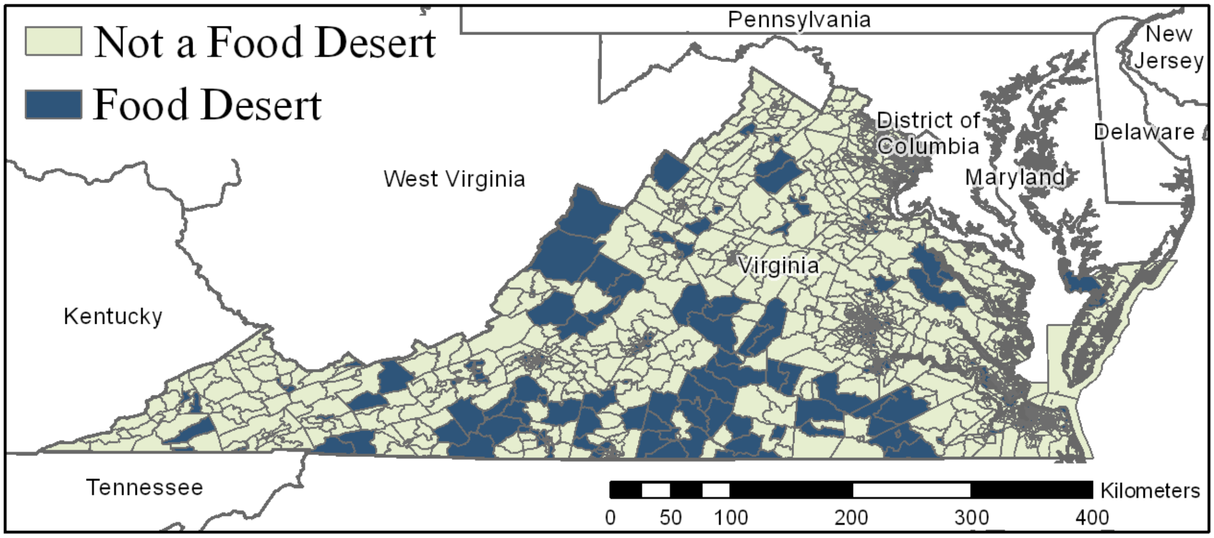

Figure 7: Map of food deserts by census tract

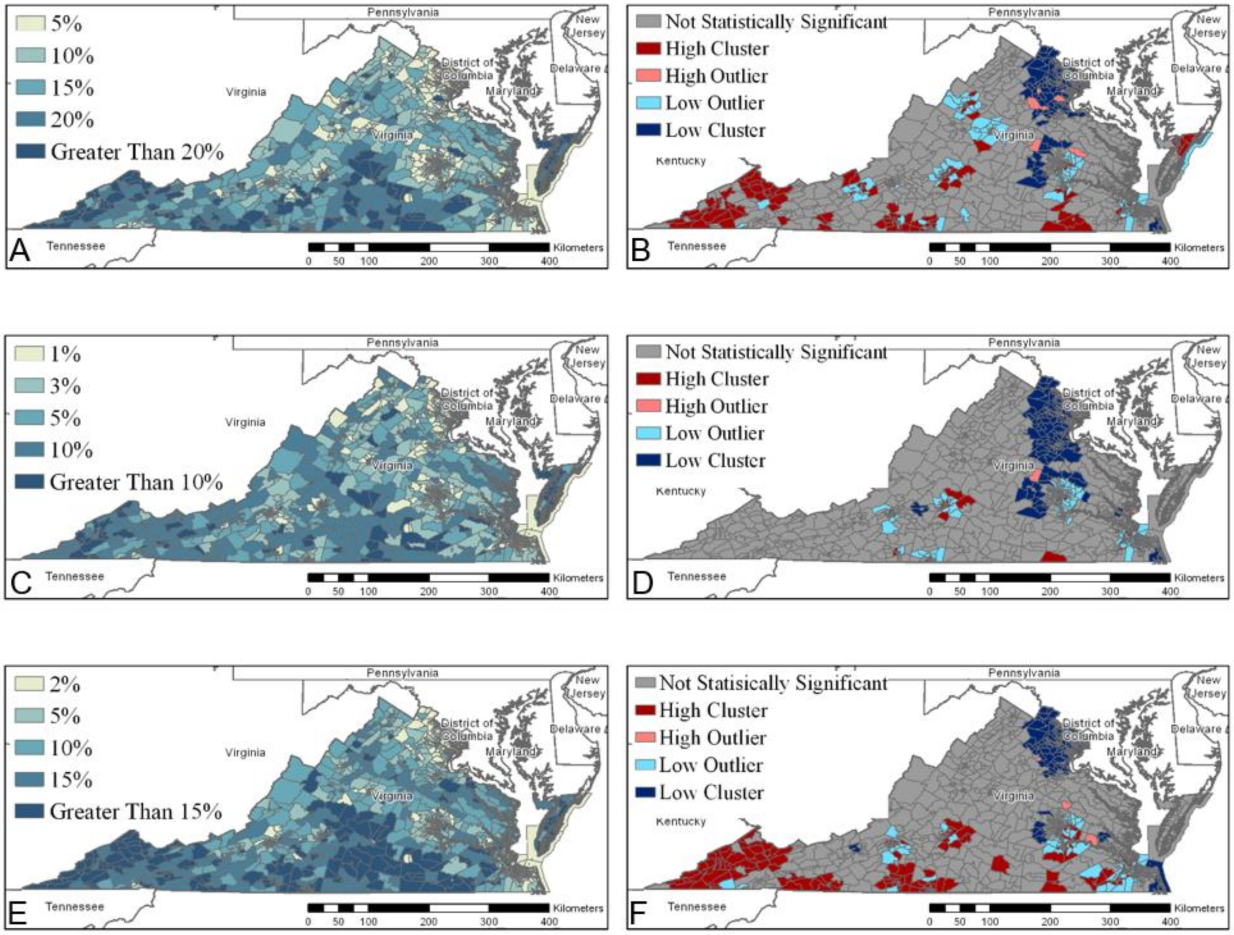

Figure 8: Map of poverty related risk factors by census tract: A) Distribution of poverty rates; B) Cluster analysis of poverty rates; C) Distribution of the rate of households without access to a vehicle; D) Cluster analysis of the rate of households without access to a vehicle; E) Distribution of the rate of households receiving SNAP benefits; and F) Cluster analysis of the rate of households receiving SNAP benefits

The analysis also shows that, on average, census tracts with VAHWQP samples have lower percentages of the population made up of children than the state average and significantly lower percentages of houses without access to a vehicle (Table 6). The percent of tracts that receive Supplemental Nutrition Assistance Program (SNAP) benefits is generally lower for tracts that participated in VAHWQP, and even lower for the high strontium concentration tracts. Census tracts with high levels of strontium have the lowest rate of households in poverty when compared to tracts with samples, tracts in the Ridge and Valley, and the state as a whole. The spatial pattern in Figure 8 and Figure 9 shows that the northern corner of Virginia is generally wealthier with more children, more vehicles, and fewer households on SNAP benefits than the rest of the state. Each measure of vulnerability indicates slightly different regions as the most vulnerable spatially, but in general, the far southwest corner of Virginia along with Greensville, Sussex, and Southampton counties are the most socially vulnerable areas.

Table 6: Summary of the social vulnerability analysis

	Percent of Census Tracts in VA	Percent of Census Tracts in Ridge and Valley	Percent of Tracts Participating in VAHWQP	Percent of Tracts with High Strontium Samples
High Poverty Rate	23.174	21.824	12.958	11.594
High Rate of Households on SNAP Benefits	23.174	20.521	13.239	2.899
High Rate of Households without a Vehicle	16.836	5.863	3.803	0.000
High Percentage of Population Under 18	26.927	5.863	23.380	11.594
Classified as Food Desert	15.010	18.567	14.648	20.290

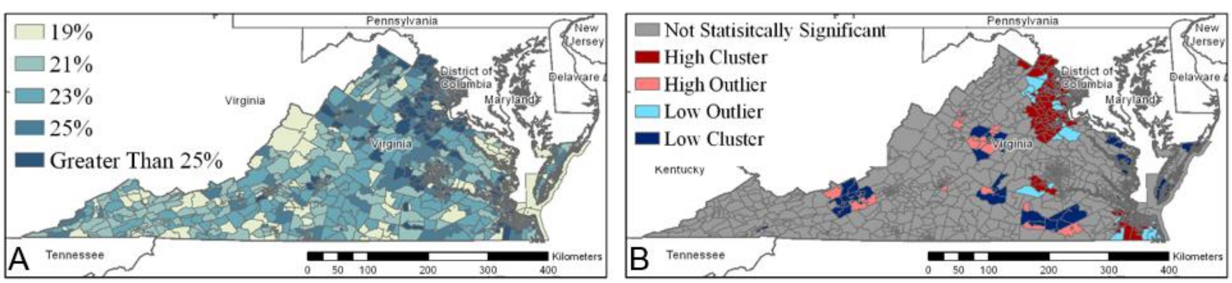

Figure 9: A) Map of the percentage of the population under the age of 18; and B) Map of cluster analysis of the percentage of the population under the age of 18

3.5 Discussion

Only 1.2% of PDW samples exceed the proposed EPA RHL (1.5 mg/L) for strontium. While the low number of high strontium samples suggests that most Virginians are safe from strontium contamination, the linear cluster pattern indicates that individuals living in the Ridge and Valley province (e.g., Augusta, Fredrick, Highland, Montgomery, Shenandoah, and Wythe) who rely on private drinking water have a higher probability (3.5%) of exceeding the proposed EPA RHL. There is also a cluster of high concentrations of strontium around Prince William County. After examining further, it is clear that Prince William County has high rates of calcium, magnesium, and hardness, which is very similar to the Ridge and Valley.

There are also 2,350 PDW samples collected from households using water softeners. Of these samples, 1.2% of them exceed the proposed EPA RHL (1.5 mg/L) for strontium. While the number of high strontium samples with water softeners mirrors that of the whole group, it is important to note that near one quarter of the samples are using water softeners that reduce the amount of strontium in the water.

The four land cover types with the greatest occurrences of high concentrations of strontium are hay/pasture, deciduous forest, developed open space, and developed low intensity, most of which are a product of human-environment interaction. This suggests that certain types of human development may impact strontium concentrations in drinking water as hay/pasture, developed open space, and developed low intensity land cover types account for 81% of the high strontium samples. It is important to note that high intensity development land cover had no high strontium samples. However, this is likely because most homes in that land cover type are on public water systems and therefore did not participate in this study. Agriculture (cultivated crops and hay/pasture), another land cover defined by human intervention, does not have a large impact on strontium as less than half (42.5%) of the high strontium samples fall on agricultural land. This indicates that phosphate fertilizers are not having a large impact on strontium concentrations in drinking water. Unfortunately, we do not know if phosphate fertilizers are widely used in Virginia, which could account for why we do not see a large impact from agricultural land use. It is worth noting that VAHWQP collects drinking water samples, most of which are taken from inside the house and not the field well. The land cover imagery resolution is 30m x 30m, so it is possible that there is agricultural land use near the PDW source, but not directly adjacent to the sample location. This would cause an underreporting of the impact of phosphate fertilizer on strontium concentrations in PDW. While we see high rates of occurrence in areas impacted by human intervention, these areas only account for around 80% of the high strontium samples and more work would need to be done to determine if the physical risk is connected to fertilizer use.

The five most common rock types--limestone, dolomite, sandstone, shale, and black shale account for 90% of the high concentration samples and follow a similar spatial pattern as the VAHWQP sample data. This indicates that geology has an influence on strontium concentrations. Unfortunately, there is no way to determine what the geology of the source aquifer is because well depths are unknown for about half (47%) of the samples, and the geology is complex enough to make predicting the source rock difficult without knowing both the exact well location and the well depth. The spatial pattern of the most common rock types is similar to the spatial pattern of the high strontium samples and the Ridge and Valley province, indicating a relationship between the three. Therefore, this study finds a link between rock type and strontium, but cannot indicate if those rock types are the source of the strontium. However, it does indicate a high physical vulnerability for individuals whose wells are located on those particular rock types.

While physical vulnerability factors follow the Ridge and Valley province, social vulnerability factors follow a different pattern. Data indicate that the southwest corner of the state (Appalachian Plateau) and Greensville, Sussex, and Southampton counties have unusually high rates of poverty, defined here as federal poverty rates, percent of households collecting SNAP benefits, and percent of households without access to a vehicle. We also see that census tracts in northern corner of the state have the highest percentage of children in the population and are also relatively wealthy. Less than 6% of census tracts in the Ridge and Valley have a high percentage of children in the population, compared to 23% for all VAHWQP participants and 11% for high strontium sample census tracts. Likely, census tracts with higher percentages of children participate in VAHWQP at greater rates as a bias of where the program hosts workshops while the census tracts that have relatively greater incomes would be more motivated to participate in VAHWQP due to the financial freedom to fund participation. Additionally, locations where VAHWQP samples were collected have low poverty rates, low SNAP benefit use, and low rates of households without access to a vehicle. This is likely a result of the social demand of participating in VAHWQP, including attending meetings and returning samples to specified locations at specific times. Since both poverty and percentage of children appear to be biased by sampling, no conclusions can be drawn on their impact. The only factor that revealed social vulnerability in areas of high strontium was food deserts. This is significant because access to a good diet (high in calcium and protein) is essential to counteract the adverse health impacts of ingesting excess strontium.

3.6 Conclusion

With 1.7 million Virginians relying on private water systems and few knowing the water quality, there is a need to understand the public health risks these residents may face. Strontium has the potential to cause long lasting damage to children's health, but since it is simple to remove, it is critical to inform residents of their vulnerabilities so they can mitigate the risks and keep their families safe. In this work, we provided initial constraints on the distribution and spatial associations of strontium in PDW to provide this information to the public.

This study found that individuals living in the Ridge and Valley had the highest physical vulnerabilities to elevated strontium in their drinking water. The prevailing rock types in the region are also rock types that can contain high strontium. This study postulates that when those rock types are present, there is greater vulnerability to strontium contamination in drinking water. That said, human intervention was also linked to high concentrations of strontium, but this is likely due to a sampling bias and further work needs to be conducted to examine the impact of human interventions on strontium in drinking water. In general, households with high levels of strontium do not have higher social vulnerability to strontium compared to the state average, with the exception of higher rates of living in food deserts. Even without receiving test results about the concentration of strontium in drinking water, individuals will know the factors that increase their vulnerability to the health impacts of strontium. The information in this study will be applied at VAHWQP to inform participants of their vulnerability.

4. Conclusion

Water is ingrained in every aspect of society, and safe drinking water is essential for securing a healthy and economically productive life. In the United States, most citizens obtain drinking water from public sources that are protected under the SDWA (Dieter et al., 2018). However, there is no federal agency that regulates, tests, monitors, maintains, or treats drinking water for the remaining 13 million households that rely on private water supply systems (EPA, 2018). In Virginia, more than 20% of residents (about 1.7 million citizens) obtain drinking water from private systems (typically wells, but also springs and cisterns), and most do not know the quality of their water (Benham et al., 2016). In fact, most (80%) of households with PDW have at most tested their water quality only once.

One contaminant threatening the safety of drinking water is strontium, which was recently recognized as a public health concern. Strontium was proposed as a new regulated substance in the SDWA Third Drinking Water CCL (United States EPA, 2014) and meets the requirements for inclusion: it was shown to have an adverse health effect; is known to occur in public water systems; and it was determined to present a meaningful opportunity to reduce health risk. However, no decision has been made as of submission of this paper to regulate strontium.

Research on PDW is somewhat limited, especially when it comes to large scale studies in the United States. Even with the EPA's acknowledgement of the risks of strontium in drinking water and the potential to improve public health, there are very few studies that investigate strontium in PDW and none in Virginia. This research is the first study in Virginia to gather strontium data from PDW (at a large scale. Furthermore, this is the first study to analyze statistically, geospatially, and descriptively which factors influence strontium concentrations and which populations are most physically and socially vulnerable to contamination.

This paper investigated three research questions in order to glean essential information on strontium in PDW:

1. What is the level of strontium in private drinking water systems in Virginia?

2. What are the physical vulnerabilities to strontium contamination in private drinking water systems in Virginia?
3. What are the social vulnerabilities to strontium contamination in private drinking water systems in Virginia?

We found that the level of strontium is generally low with only 2% of samples statewide exceeding the proposed RHL of 1.5 mg/L. This puts approximately 28,000 of the 1.7 million individuals relying on PDW at risk. Additionally, nearly 25% of samples used water softeners that reduce the concentration of strontium in their drinking water. More samples collected before treatment would help clarify the patterns and relationships in a uniform way. Even though less than 2% of the samples had concentrations hazardous to health, the majority of the 120 high strontium samples are clustered in the Ridge and Valley province. There are more than 1.3 million people who live the in the Ridge and Valley province in Virginia who are vulnerable because they likely get their water from the same water sources found to have high strontium. In the future, a study examining strontium in public water could more directly identify the physical vulnerability that individuals relying on public water face. The Ridge and Valley province extends outside the bounds of the state of Virginia into Alabama, Georgia, Tennessee, West Virginia, Maryland, Pennsylvania, and New York. Thus, since the physical characteristics continue outside the bounds of Virginia, individuals in those states might also be vulnerable to strontium contamination. A future study investigating PDW quality in these neighboring states would help identify who and how many are at risk.

Rock-type in the Ridge and Valley province also plays a role in physical vulnerability to strontium contamination in Virginia. Limestone, dolomite, sandstone, and shale, are strongly correlated with high strontium concentrations and follow a similar spatial pattern as the high strontium sample distribution. Together, these findings indicate that the presence of limestone, dolomite, sandstone, and shale increases vulnerability to strontium contamination. This study was limited, however, because data on composition of the PDW source rock is mostly absent. Thus, we recommend a follow-up study that investigates strontium concentrations of known aquifers (where source rock is documented) to help scholars and residents better understand the source of strontium in drinking water.

The relationship between land use and strontium is much more complex. Land use types defined by human intervention are correlated with high concentrations of strontium, but this is likely the result of sampling bias and unknown factors related to phosphate fertilizer use in agriculture. Future research investigating the concentration of strontium in drinking water from farms that use phosphate fertilizers and control farms that do not could parse out the impact of phosphate fertilizer on strontium concentrations in PDW in Virginia.

Social vulnerability to the health effects of strontium is high in various regions of Virginia. The health effects of high strontium can be mitigated by a diet high in calcium and protein, which is less likely to be achieved in households below the poverty line or households located in a food desert. In Virginia, the southwest region of the state as well as Greensville, Sussex, and Southampton counties experience high poverty rates defined by federal poverty levels, Supplemental Nutrition Assistance Program (SNAP) benefit use, and households that do not have access to a vehicle. Another factor that increases social vulnerability to the health effects of strontium is youth population. This is because children absorb more strontium and are subject to strontium substitution in bone growth. Interestingly, while the northern corner of the state has the highest concentrations of children, it is also an urbanized with fewer people on private water systems and is a relatively wealthy region of the state and thus the social vulnerabilities to strontium contamination (i.e., poverty and a diet low in calcium and protein) are mitigated. Food deserts, areas without geographical and economic access to nutritious diets (e.g., such as those containing high calcium and protein) were most commonly found in the regions where high strontium concentrations were found. Ultimately, many people in Virginia are socially vulnerable to strontium, but the Ridge and Valley province exhibits the highest social vulnerability due to the presence of food deserts and high rates of poverty. Since this information is collected at the census tract level, we can only make assumptions about larger trends of vulnerability. In the future, income, government benefit collection, vehicle access, and family size/youth population data collected at each sample site would allow for more precise analyses of social vulnerability as well as more actionable recommendations.

This research can assist individuals who rely on PDW in Virginia understand how they might be vulnerable to the health impacts of high strontium levels and take actions to protect themselves and their families. However, the broader impacts of this research are far reaching and impact more than those who rely on PDW in Virginia. For example, all households that use PDW in the United States, and especially those in states adjacent to Virginia (e.g., Alabama, Georgia, Tennessee, West Virginia, Maryland, Pennsylvania, and New York) that contain part of the Ridge and Valley, a physically vulnerable region, of could be informed by this research. Additionally, since a portion of municipal drinking water provided by local water authorities in the Ridge and Valley is sourced from groundwater, other citizens are often consuming the same initial water as PDW consumers. Thus, individuals consuming public water supplies in the Ridge and Valley province are also physically vulnerable to strontium contamination. This again underscores the critical need for strontium to be included in the EPA SDWA.

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Appendix A: Full Tables

Table 7: Full results of land use analysis

	All Pixels in Virginia	All Ridge and Valley Pixels	% Occuring in Ridge and Valley	All VAHWQP Samples	All High Strontium VAHWQP	% Occuring on High Samples
Developed, High Intensity	315984	63236	20.012	11	0	0.000
Barren Land	338178	51750	15.303	8	0	0.000
Developed, Medium Intensity	984856	210559	21.380	48	1	2.083
Emergent Herbaceuous Wetlands	995892	3209	0.322	28	0	0.000
Herbaceuous	2239702	500955	22.367	97	2	2.062
Open Water	2609287	157954	6.054	29	0	0.000
Developed, Low Intensity	2776031	719308	25.911	543	10	1.842
Shrub/Scrub	2961368	80029	2.702	273	0	0.000
Mixed Forest	4091379	816657	19.960	236	0	0.000
Cultivated Crops	4912780	302283	6.153	658	6	0.912
Woody Wetlands	5081862	9996	0.197	172	1	0.581
Developed, Open Space	6806563	1563401	22.969	1684	20	1.188
Evergreen Forest	11723582	1386292	11.825	455	5	1.099
Hay/Pasture	19752866	7357204	37.246	2624	45	1.715
Deciduous Forest	51494647	18284969	35.508	2764	30	1.085
Total	117084977	31507802	26.910	9630	120	1.246

Table 8: Full results of rock type analysis

Rock Type	All Virginia Occurrences	Area of Rock Formation in Virginia	Ridge and Valley Occurrences	Area of Rock Formation in Ridge and Valley	Percent of Formation Area in Ridge and Valley	All VAHWQP Occurrences	Area of Rock Formation on VAHWQP	High Strontium VAHWQP Occurrences	Area of Rock Formation on High Strontium Samples	Percent of Formation Area on High Strontium Samples
Alkali Syenite	5	0.015	0	0.000	0.000	2	0.011	0	0.000	0.000
Alluvium	118	0.115	0	0.000	0.000	12	0.051	1	0.043	83.900
Amphibolite	158	0.181	0	0.000	0.000	33	0.136	0	0.000	0.000
Anorthosite	2	0.004	0	0.000	0.000	1	0.003	1	0.003	100.000
Arenite	70	0.139	65	0.130	93.490	2	0.001	0	0.000	0.000
Augen Gneiss	62	0.171	0	0.000	0.000	22	0.156	0	0.000	0.000
Basalt	25	0.014	4	0.000	0.664	6	0.012	0	0.000	0.000
Beach Sand	50	0.017	0	0.000	0.000	2	0.004	0	0.000	0.000
Biotite Gneiss	112	0.880	0	0.000	0.000	40	0.851	0	0.000	0.000
Black Shale	98	0.186	97	0.185	99.863	17	0.145	2	0.094	65.052
Breccia	5	0.004	0	0.000	0.000	2	0.003	0	0.000	0.000
Clay Or Mud	200	0.079	0	0.000	0.000	9	0.030	0	0.000	0.000
Conglomerate	87	0.051	0	0.000	0.000	21	0.032	1	0.006	17.679
Diabase	25	0.041	0	0.000	0.000	3	0.039	0	0.000	0.000
Diorite	6	0.013	0	0.000	0.000	2	0.011	0	0.000	0.000
Dolostone (Dolomite)	234	0.655	223	0.650	99.332	82	0.599	15	0.196	32.668
Dune Sand	4	0.004	0	0.000	0.000	2	0.003	0	0.000	0.000
Felsic Gneiss	17	0.064	0	0.000	0.000	7	0.063	0	0.000	0.000
Felsic Metavolcanic Rock	8	0.010	0	0.000	0.000	4	0.007	0	0.000	0.000
Felsic Volcanic Rock	52	0.114	0	0.000	0.000	9	0.077	0	0.000	0.000
Gabbro	15	0.015	0	0.000	0.000	2	0.011	0	0.000	0.000
Gneiss	76	0.155	2	0.020	13.120	32	0.132	0	0.000	0.000
Granite	260	0.493	5	0.007	1.403	62	0.398	0	0.000	0.000
Granitic Gneiss	138	0.168	11	0.015	8.677	41	0.129	0	0.000	0.000
Granodiorite	23	0.052	12	0.049	93.703	7	0.046	0	0.000	0.000
Granulite	86	0.115	0	0.000	0.000	22	0.090	0	0.000	0.000
Gravel	487	0.905	0	0.000	0.000	134	0.699	0	0.000	0.000
Greenstone	20	0.039	0	0.000	0.000	6	0.027	0	0.000	0.000
Limestone	223	0.455	216	0.454	99.859	50	0.346	13	0.181	52.235
Mafic Gneiss	21	0.033	2	0.005	14.159	5	0.030	0	0.000	0.000
Mafic Metavolcanic Rock	58	0.063	9	0.079	125.507	12	0.047	0	0.000	0.000
Mafic Rock	11	0.001	0	0.000	0.000	1	0.000	0	0.000	0.000
Marble	44	0.007	0	0.000	0.000	1	0.000	0	0.000	0.000
Melange	19	0.097	0	0.000	0.000	11	0.089	0	0.000	0.000
Meta-Argillite	97	0.499	0	0.000	0.000	39	0.478	1	0.175	36.498
Meta-Basalt	55	0.194	0	0.000	0.000	13	0.174	0	0.000	0.000
Metamorphic Rock	8	0.006	0	0.000	0.000	2	0.003	0	0.000	0.000
Metasedimentary Rock	40	0.047	0	0.000	0.000	15	0.037	1	0.002	6.595
Metavolcanic Rock	40	0.144	0	0.000	0.000	10	0.137	0	0.000	0.000
Mica Schist	42	0.233	0	0.000	0.000	14	0.211	0	0.000	0.000
Monzonite	3	0.003	0	0.000	0.000	1	0.002	0	0.000	0.000
Mylonite	40	0.152	1	0.000	0.320	14	0.138	1	0.002	1.179
Norite	23	0.022	0	0.000	0.000	5	0.014	0	0.000	0.000
Orthogneiss	3	0.003	0	0.000	0.000	2	0.002	0	0.000	0.000
Paragneiss	31	0.086	0	0.000	0.000	7	0.084	0	0.000	0.000
Pelitic Schist	22	0.025	0	0.000	0.000	3	0.014	0	0.000	0.000
Peridotite	1	0.000	1	0.000	100.000	0	0.000	0	0.000	0.000
Phyllite	89	0.149	3	0.001	0.909	17	0.101	0	0.000	0.000
Phyllonite	2	0.006	0	0.000	0.000	1	0.006	0	0.000	0.000
Quartz Monzonite	5	0.048	0	0.000	0.000	1	0.047	1	0.047	100.000
Quartzite	111	0.130	26	0.111	85.235	25	0.112	0	0.000	0.000
Rhyolite	17	0.010	0	0.000	0.000	3	0.001	0	0.000	0.000
Sand	695	1.133	0	0.000	0.000	171	0.856	0	0.000	0.000
Sandstone	557	0.694	268	0.455	65.546	72	0.346	9	0.049	14.031
Schist	98	0.070	0	0.000	0.000	25	0.053	0	0.000	0.000
Sedimentary Breccia	11	0.010	0	0.000	0.000	2	0.007	0	0.000	0.000
Serpentinite	3	0.002	0	0.000	0.000	1	0.002	0	0.000	0.000
Shale	468	1.341	394	1.268	94.505	101	1.039	12	0.296	28.524

Table 9: Continuation of Table 8

Rock Type	All Virginia Occurrences	Area of Rock Formation in Virginia	Ridge and Valley Occurrences	Area of Rock Formation in Ridge and Valley	Percent of Formation Area in Ridge and Valley	All VAHWQP Occurrences	Area of Rock Formation on VAHWQP	High Strontium VAHWQP Occurrences	Area of Rock Formation on High Strontium Samples	Percent of Formation Area on High Strontium Samples
Slate	28	0.03846698	0	0	0	7	0.035424515	0	0	0
Terrace	9	0.01780993	0	0	0	3	0.012151094	0	0	0
Tonalite	27	0.020333804	0	0	0	4	0.011733989	0	0	0
Ultramafic Rock	41	0.003990561	0	0	0	4	0.001873352	0	0	0
Ultramafitite	13	0.000765926	0	0	0	1	2.75404E-05	0	0	0
Water	305	1.341087011	14	0.003606107	0.268894331	25	1.304251315	1	0.00138051	0.105846935
Total	423	1.422454211	14	0.003606107	0.253513042	44	1.365461806	1	0.00138051	0.101102062

Table 10: Full results of rock age analysis

Rock Formation Age	All Virginia Occurrences	Area of Rock Formation in Virginia	Ridge and Valley Occurrences	Area of Rock Formation in Ridge and Valley	Percent of Formation Area in Ridge and Valley	All VAHWQP Occurrences	Area of Rock Formation on VAHWQP	High Strontium VAHWQP Occurrences	Area of Rock Formation on High Strontium Samples	Percent of Formation Area on High Strontium Samples
Proterozoic	203	0.639	0	0.000	0.000	43	0.556	0	0.000	0.000
Proterozoic-Paleozoic	2	0.006	0	0.000	0.000	0	0.000	0	0.000	0.000
Proterozoic Z	345	0.756	3	0.001	0.179	106	0.632	1	0.002	0.389
Proterozoic Z-Cambrian	504	0.960	9	0.079	8.182	99	0.858	1	0.175	20.348
Proterozoic Z-Ordovician	7	0.081	0	0.000	0.000	6	0.081	0	0.000	0.000
Proterozoic Z-Pennsylvanian	8	0.007	0	0.000	0.000	1	0.003	0	0.000	0.000
Proterozoic Y	474	0.921	32	0.096	10.375	149	0.814	2	0.051	6.219
Proterozoic Y-Pennsylvanian	35	0.023	0	0.000	0.000	6	0.014	0	0.000	0.000
Proterozoic-Paleozoic	2	0.006	0	0.000	0.000	1	0.006	0	0.000	0.000
Proterozoic - Paleozoic ?	40	0.152	1	0.000	0.320	14	0.138	1	0.002	1.179
Cambrian	591	1.396	246	0.688	49.262	162	1.148	14	0.244	21.265
Cambrian-Ordovician	148	0.375	108	0.317	84.420	46	0.338	8	0.088	26.136
Ordovician	442	0.797	374	0.726	91.050	100	0.633	13	0.269	42.536
Ordovician-Silurian	19	0.025	17	0.004	15.783	1	0.021	0	0.000	0.000
Ordovician-Devonian	10	0.002	10	0.002	100.000	2	0.000	1	0.000	27.370
Silurian	85	0.178	76	0.175	98.369	3	0.011	1	0.010	92.945
Silurian-Devonian	116	0.196	116	0.196	100.000	10	0.115	3	0.041	35.872
Devonian	168	0.631	168	0.631	100.000	46	0.472	3	0.099	20.932
Devonian-Mississippian	18	0.014	17	0.014	98.231	1	0.005	0	0.000	0.000
Mississippian	110	0.245	97	0.158	64.552	12	0.146	2	0.012	7.944
Mississippian - Pennsylvanian	8	0.007	0	0.000	0.000	2	0.004	0	0.000	0.000
Mississippian Pennsylvanian	4	0.023	0	0.000	0.000	1	0.022	0	0.000	0.000
Pennsylvanian	210	0.394	56	0.343	86.931	3	0.265	0	0.000	0.000
Pennsylvanian - Mississippian	7	0.000	4	0.000	92.964	0	0.000	0	0.000	0.000
Permian	8	0.000	0	0.000	0.000	0	0.000	0	0.000	0.000

Table 11: Continuation of Table 10

Rock Formation Age	All Virginia Occurrences	Area of Rock Formation in Virginia	Ridge and Valley Occurrences	Area of Rock Formation in Ridge and Valley	Percent of Formation Area in Ridge and Valley	All VAHWQP Occurrences	Area of Rock Formation on VAHWQP	High Strontium VAHWQP Occurrences	Area of Rock Formation on High Strontium Samples	Percent of Formation Area on High Strontium Samples
Upper Triassic	175	0.20956857	0	0	0	46	0.051488017	5	0.035269826	68.50103768
Triassic	53	0.068677294	0	0	0	14	0.155213877	2	0.0223529	14.40135429
Jurassic	28	0.043566271	0	0	0	5	0.041316865	0	0	0
Jurassic-Tertiary	4	6.67604E-05	4	6.67604E-05	100	0	0	0	0	0
Lower Jurassic	47	0.025135989	1	3.6353E-05	0.144625307	15	0.019909539	0	0	0
Cretaceous	59	0.039712032	0	0	0	10	0.018257991	0	0	0
Holocene	305	1.341087011	14	0.003606107	0.268894331	25	1.304251315	1	0.00138051	0.105846935
Tertiary	467	0.987688954	0	0	0	138	0.815430567	0	0	0
Tertiary-Quaterna	145	0.315468964	0	0	0	30	0.232357345	0	0	0
Quaternary	907	0.966274407	0	0	0	155	0.588588132	1	0.0426176	7.240648958
Total	2190	3.997246253	19	0.00370922	0.092794391	438	3.226813649	9	0.101620837	0.000232011